AN EVALUATION OF VEGETATED
ROOFING TECHNOLOGY: APPLICATION
AT AIR FORCE PLANT FOUR, BUILDING 15

THESIS

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Abstract

The United States Air Force maintains thousands of facilities around the world. Many of these facilities have asphalt built up roofs or some other less than sustainable roofing system. In an effort to find roofing systems suitable for Air Force facilities that are both economically and environmentally friendly, this thesis investigated vegetated roofing as a possible alternative to conventional roofing systems. While vegetated roofs are a relatively new roofing system, they exhibit performance qualities that seem to meet Air Force needs.

An investigation into the feasibility of vegetated roofing technology revealed that this roofing system has many positive economic and environmental characteristics that could benefit the United States Air Force and the Department of Defense. The potential use of this technology was researched specifically for application to building 15 at Air Force Plant 4 (AFP4) in Ft. Worth Texas. A combination of case studies, site visits, and a life cycle economic evaluation was used to compare vegetated roofing with conventional asphalt built up roofing that is typically used at AFP4. The research revealed multiple environmental benefits and few disadvantages. The life cycle costs combined with the environmental benefits of vegetated roofing show that this roofing system is indeed a feasible alternative for building 15. The life cycle cost of the green roof was shown to be $^1/_6$-$^1/_2$ the cost of the conventional roofing system as a net present value.

Acknowledgements

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Benjamin J. Morgan

Table of Contents

Page

List of Figures

Page

List of Tables

Table Page

AN EVALUATION OF VEGETATED ROOFING TECHNOLOGY:
APPLICATION AT AIR FORCE PLANT FOUR, BUILDING 15

I. INTRODUCTION

1.1 Overview

An investigation was conducted to determine whether a vegetated roof is more economically and environmentally feasible than a conventional asphalt built up roof for Building 15 at Air Force Plant 4 (AFP4) in Ft. Worth, Texas. Feasibility will be shown by performing an in-depth cost comparison of the two roofing systems. By comparing the cost and performance factors of a vegetated roof with those of a conventional roofing system, the best roof for Building 15 can be determined.

The type of roofing most commonly used at AFP4 is 3 and 4 ply asphalt built up roofing (Mockler, 2003). These roofs are constructed by applying alternating layers of asphalt-coated roofing felt and hot mopped tar (Cram, 2003). Each layer is considered to be one ply. A 3 ply roof is three layers of felt and tar. The top layer of asphalt on the roofs at AFP4 is usually covered with gravel, which serves two purposes. The gravel holds the roofing material in place and protects it from damage by ultraviolet sunlight. The light-colored gravel used there also reflects some of the sun's heat. Built up roofs typically last from 10 to 20 years, depending on the severity of the weather (Scheirer, 2003).

Vegetated or green roofs are essentially waterproofing membranes with multiple components above them that protect the membrane while supporting plant life. In the typical green roof, a waterproofing membrane is applied to the roof deck. If the membrane does not

have inherent root protection, a root protection barrier is applied to prevent roots from penetrating the waterproofing membrane and causing leaks. Next a drainage layer is applied to enable drainage if the plants and growing medium are saturated. A filter fabric is attached to the drainage layer to prevent soil/substrate from clogging the drainage layer. The growing medium, or substrate, is placed on the filter fabric. This medium is typically a blend of mineral rocks, sand, and organic topsoil. The vegetation, usually sedums or grasses, can be planted by hydro-seeding, inserted as plugs, or placed as pre-grown vegetated mats. The multiple layers work together synergistically to provide longer roof life, increased cooling efficiency, improved water and air quality, and enhanced management of storm water.

1.2 Background

AFP4 is a large aircraft manufacturing facility with many support facilities. The plant is owned by the Air Force (AF) and is operated by Lockheed Martin (LM). AFP4 is a complex consisting of 121 facilities where 15,000 employees work. In this type of industrial environment involving such a large number of people there are many environmental issues that arise. In an effort to promote healthy work practices while being an environmental steward, the AF decided to determine ways to make work processes more economically and environmentally effective.

The AF commissioned an architectural and community design firm, McDonough Braungart Design Chemistry (MBDC), to perform a collaborative, eco-effective assessment. This assessment would determine eco-effective opportunities at AFP4. The desired results of the MBDC survey were to: 1) identify opportunities to maximize healthy and prosperous systems based on eco-effective principles and methods, 2) outline the economic and environmental effectiveness of the opportunities, 3) develop strategies for implementation, and 4) use the

information as a platform for the AF’s environmental agenda and as an example for future surveys at other AF locations (USAF, 2003:1).

A primary area identified for improvement by MBDC and LM was that of minimizing storm water runoff. Storm water erodes soils and carries silts and pollutants into local water systems which degrade water quality. This issue is due in large part to the fact that AFP4 has 7.2 million square feet of roof space and 14,000 parking spaces for LM employees (USAF, 2003:3). The massive rooftop areas coupled with the paved parking surfaces and streets create an enormous impervious surface that does not allow rainwater to immediately enter the ground, causing storm water runoff problems.

LM is also concerned with the maintenance, repair, and replacement of these vast roofing systems. Problems with the roof over an aircraft assembly plant can be very costly. Leaks have the potential to cause delays within certain processes in the production lines. Delays in production equate to dollars lost. Maintenance can be costly and leaks have been an issue in the past (Harrison, 2003). Measures to repair leaks or to prevent future problems on such vast roofs are a costly endeavor.

The failure mode of the roof is due to the deterioration of the roofing membrane. This deterioration is due to two main causes: exposure to the sun’s ultraviolet rays and to the expansion and contraction caused by temperature extremes that are common to the Ft. Worth area (USAF, 2003:5,9; Scholz-Barth, 2001:6). The rapid rise in temperature during the day heats the roof quickly causing the membrane to expand. Then the membrane contracts as the roof cools in the evening. Over time, this stretching and shrinking degrades the membrane’s structural integrity. Another factor that causes damage to the membrane is the difference between interior and exterior temperatures. One side of the membrane is a different temperature

than the other. This causes uneven thermal stress which weakens the membrane. The effects of this movement over time contribute to the failure of the membrane.

Within the next five years, over 1.6 million square feet of roofing at AFP4 will need to be replaced, (USAF, 2003:6) including the roofing on Building 15. LM intends to replace the current roofs with new roofing systems of the highest quality (USAF, 2003:6). LM has established six criteria for selecting the replacement roofing systems (USAF, 2003:6). The criteria are listed in the order of importance:

1. Longevity
2. First Cost
3. Traffic Resistance
4. Hail Resistance
5. Expected normal maintenance cost
6. Availability of contractors experienced with the system

Based on LM's roof selection criteria for replacing roofs and the need for effective storm water management, MBDC suggested a green roof as an effective means to address both issues (USAF, 2003:6). The suggestion of storm water control using innovative methods and the deterioration of the current roofing systems presents a unique opportunity to evaluate a vegetated roof system. However, green roof technology is new to the United States and is not commonly understood. With green roofing systems being relatively new products in the roofing industry, users are skeptical of them because they are not familiar with the performance of these systems. LM wants to verify that this roofing system is feasible for use in the Ft. Worth area before installing it on multiple facilities.

1.3 Problem

The specific problem for this research effort is to determine if a vegetated roof is more economically and environmentally feasible than a conventional asphalt built up roof for Building 15 at AFP4. The conclusions drawn from the roof system comparison will determine feasibility. In order to effectively compare the two roofing systems, the thesis examination will consider life cycle costs, the overall environmental impact of the roof, and its performance effectiveness when compared to a conventional roof. An effort will be made to determine if green roofs ultimately enhance the environment while proving to be a more cost effective roofing system over the life of the roof.

This thesis will attempt to answer the following questions: 1) Where have green roofs been used successfully in the past and what are the characteristics, benefits, and problems encountered with those roofs? 2) What is a viable green roof design for Building 15 at AFP4 based on successful green roof applications and the recommendations of experts in the green roof industry? 3) What is the life cycle cost of a green roof and the conventional roofing system that would be used at AFP4? 4) What are the anticipated characteristics, benefits, and maintenance requirements for a green roof at AFP4?

1.4 Scope

The analysis of the green roofing systems will be tailored specifically to an application on Building 15 at AFP4. From this analysis, a comparison can be made between the green roof system and the conventional roofing system being considered for Building 15.

The scope of this study is limited to data collection at AFP4 and several select sites. However, the methodology applied for this analysis and the life cycle cost formulas that are

developed may be applied to other scenarios to determine the feasibility of green roof installations at military and civilian sites. The goal of this research is to develop a clear and precise analysis of green roof systems that are feasible in AF applications.

1.5 Approach/Methodology

Green roofs are relatively new to the United States. For this reason, there is very little documented performance data for green roofs. To accurately perform the feasibility study for Building 15, case studies and a life cycle assessment will be performed. First, case studies will be performed on two green roofs within the United States – Chicago City Hall and Ford Motor Company's new truck manufacturing plant in Dearborn, Michigan. Data will be collected from these facilities including: the components of the installed green roof, energy consumption, installation and maintenance costs, storm water runoff measurements, as well as any improvements to the microclimate.

The same type of information will be gathered from case studies of multiple facilities in Germany. Many green roofs in Germany have been in existence for long periods of time and will provide information about the long term performance of green roofs. With so many roofs in Germany, there is a great deal of variance in the roofs. This variance in roofs will provide insight into additional benefits as well as potential problems.

The information gathered in the case studies, in addition to expert opinion, will be used to determine what green roofing components and design will produce the best roof for Building 15. Once the best roof design for Building 15 is determined and a cost estimate is developed, analyses will be performed to compare this type of green roof and the conventional system that

would be used. This will enable the comparison of both economic and environmental impacts of green roofs and conventional roofing systems.

When comparing the economic factors for both roofs, some costs lend themselves to a simple comparison, while other costs are not as easily defined. Factors such as the cost of initial construction, maintenance and repairs, and the longevity of the roofing system can be directly attributed to the roof itself. However, green roofs also indirectly contribute to cost savings for a facility. The synergistic effects of the green roof reduce cooling costs in the summer. The vegetation provides shading for the roof surface, and the multiple components of a green roof produce an insulating effect. This decreases the energy consumption for the facility and translates into dollars saved. Green roofs also reduce storm water runoff which can create pollution problems. These issues have costs associated with them, as well. However, these costs can be difficult to ascertain. Only those costs that can be reasonably determined will be used in the comparison of the two roofing systems.

1.6 Significance

The research effort will determine the best roofing system to be installed at an Air Force facility. This endeavor in itself is significant. However, the true importance of this project is the ability to apply a consistent methodology to an evaluation of any AF or civilian facility to be retrofitted or designed with a green roof system.

II. LITERATURE REVIEW

2.1 Introduction

Vegetated roofs are part of an emerging technology in America that emphasizes sustainable development to benefit people and the environment. Vegetated roofs, or green roofs as they are more commonly referred to, provide many economic and environmental benefits that have piqued the interest of USAF engineers. The AF is interested in capitalizing on these benefits, but wants to ensure green roofs are a preferable alternative to conventional roofing systems. This Literature Review examines some of the issues that have caused the AF and commercial entities to consider implementing green roof technology. The appealing benefits of vegetated roofs and the disadvantages that may deter their implementation will be discussed.

2.2 Sustainability

The properties of green roofs are in line with an effort to make construction designs and practices more sustainable. "Sustainable Development" refers to a system or process that causes no overall net burden or deficit to the environment. As defined by the World Commission on Environment and Development (The Brundtland Commission), sustainable development is "the capacity to meet the needs of the present without compromising the ability of future generations to meet their own needs" (US Dept. of State, 2002). Development needs to go beyond economic issues to encompass the full range of social and political issues that define overall quality of life (US Dept of State, 2002:2). Basically, sustainable development refers to implementing a system that uses renewable resources to function, as opposed to non-renewable resources, causes no lasting harm to the environment, and may improve the environment in some way.

William McDonough and Michael Braungart of McDonough Braungart Design Chemistry (MBDC) are leaders in the field of sustainability. Their goal is to try to model nature as closely as possible in any new construction designs that are developed. Nature does not create anything that it does not use. They argue that sustainable designs will be attained if we can live by the idea that "waste equals food" (McDonough and Braungart, 2002:92). McDonough and Braungart advocate the use of a resource in a way that does not ultimately burden the environment during its life cycle. There are many technologies and concepts that are being improved in an effort to allow society to become more sustainable. Some of these technologies are discussed below.

2.2.1 Alternative Energy

Sustainability can be implemented in other green building initiatives including the selection of the building energy supply. Alternative energy sources such as photovoltaic cells and wind sources are close to being sustainable. The sun is the world's primary source of energy, and efforts are being made to capture the sun's energy by more efficient means. Photovoltaic (PV) cells are one means of efficiently harnessing the sun's energy. Using photovoltaic cells to capture solar power potentially has much less impact on the environment than producing energy in traditional ways. PV cells convert light directly into electricity. As light strikes a PV cell, electrons are dislodged, creating an electric current (SEPA, 2003). By assembling these cells into panels, enough electricity can be generated to power appliances, homes, and even industrial operations. The cost of PV cells has fallen 90% since the 1970s, and they are commonly used in calculators and wrist watches today (SEPA, 2003). However, PV cells are still somewhat expensive compared to conventional power sources (SEPA, 2003). Even

though their cost causes the electricity they produce to be more expensive than that produced by traditional means, their popularity is increasing. In several developing countries in Latin America, PV cells are being used as an energy source in remote villages – some receiving electricity for the first time (NREL, 2003). PV cells are becoming more popular in developed countries as well; the Chicago Center for Green Technology incorporates PV cells on its green roof, taking advantage of the clean, free, and sustainable solar energy.

Solar energy supplies another viable alternative energy source in the form of wind. As the sun heats air masses, they begin to rise. This phenomenon coupled with topography creates the winds and air currents on the earth. As of August 2003 thirty-two US states were utilizing wind as a power source (AWEA, 2003). The AF has also begun taking advantage of this sustainable resource through the use of wind turbines. One of the first AF sites that installed wind turbines was Grassmere radar site in northern Idaho (Gray, 1996:1). The energy generated by the wind turbines will be used to alleviate or augment the use of diesel powered generators saving fuel costs and reducing air emissions. This is one example of the AF incorporating sustainability into its everyday activities.

2.2.2 Living Machines

While the AF has not embraced living machines yet, the concept exudes sustainability. A living machine is a naturally functioning system designed and orchestrated by humans for specific purposes. Living machine designs are based on basic principles that are derived from the functioning laws of nature. These living machines are self-contained entities powered by the sun with the purpose of turning some form of waste, such as raw sewage, into a resource. They are made up of many living organisms – microscopic and macroscopic animals, algae, flowers,

trees, and bacteria - that are interdependent (Todd, 1994:xvii). The organisms break down waste produced elsewhere while simultaneously producing waste/food for another organism within the contained ecosystem. Essentially, living machines mimic the recycling and cleansing abilities of natural aquatic systems (Todd, 1994:xvii). They are capable of inexpensive and environmentally safe water treatment.

2.2.3 LEED

The AF has realized the need to incorporate environmentally-friendly concepts into its new facilities. In an effort to ensure new environmentally-responsible technologies are included in designs, the AF adopted LEED, the Leadership in Energy & Environmental Design Green Building Rating System (USAF, 2001). LEED was developed by the U.S. Green Building Council (U.S. Green Building Council, 2003). LEED emphasizes indoor environmental quality, conservation of resources, increased energy efficiency, as well as sustainable site development. These initiatives are implemented through state-of-the-art construction strategies that are based on well-founded scientific standards (USGBC, 2003). By adopting these standards, the AF is directing that during any new construction or major renovation, environmental concerns will be taken into consideration. LEED-EB (existing building) is a set of performance standards for existing facilities that helps them become more sustainable and energy efficient by evaluating and modifying processes and functions within the building. By incorporating the suggested measures, the AF is officially endorsing environmental stewardship and the concept of sustainability.

2.3 Background on AFP4 Green Roof

In November 2002 the AF commissioned an architectural and community design firm, McDonough Braungart Design Chemistry (MBDC), to perform an assessment highlighting eco-effective opportunities at AFP4 (USAF, 2002:1). The assessment identified vegetated roofing as an environmentally sound means to address concerns about the need to replace vast amounts of roofing and environmental concerns about storm water runoff (USAF, 2002:6). Vegetated roof systems also appeared to satisfy the majority of the criteria Lockheed Martin (LM) had established for selecting future roofing systems. After vegetated roofs were identified in the assessment, the AF began looking into this new roofing system as a possible alternative for roof replacement.

Upon deciding to consider a green roof as a possible roofing alternative, LM engineers suggested Building 15 as an adequate roof for a test case. The facility does not house aircraft assembly operations, and the green roof installation would not interrupt production activities if the green roof did not function adequately. The roof has an area of 101,430 ft^2 (Harrison, 2003) which is large enough to easily observe some of the environmental improvements that green roofs provide. After the facility was suggested for the roof installation, information gathering efforts began in order to obtain a green roof design and cost estimate for Building 15.

The cost estimate that was developed was an integral part of showing the feasibility of a green roof for Building 15. A life cycle economic analysis (LCEA) was the key component of this feasibility study. Green roofs typically have a higher first cost, but the LCEA showed that over the life of the roof, a green roof is a better economic alternative. A net present value was used to show the cost of each roofing system being considered for Building 15. Environmental benefits of vegetated roofs were illustrated and discussed, but were not a part of the economic

evaluation. The AF is striving to be more environmentally conscious, but many times acquisition decisions are justified based strictly on lowest first cost instead of life cycle costs or a cost benefit analysis.

2.4 Conventional Roofing

2.4.1 History

Some type of quality roof is vital to any facility. Without a quality roof, buildings deteriorate, and businesses can experience costly work delays. Typically, users look for several fundamental characteristics when installing a roof. Users want a roof that has a low installation cost, little or no maintenance, a long roof life, and good thermal insulating properties. Recognizing these desires, the roofing industry in the US continually strives to improve performance in these areas.

Roofing in the US has undergone a lot of change throughout history. In 1607, thatched roofs consisting of clay and straw were most common. Wood shingles, slate, and tile were also used but to a lesser degree (Cram, 2002). In the 1700s copper and flat tin became more common. In 1802 the first shingle machine was invented and drastically changed the roofing industry. By the mid 1800s the predecessor to today's built up roof (BUR) had been developed. This roof was made of coal tar and felt rolls. The coal tar was a waste product while the felt rolls were made from rags or paper. By the 1950s asbestos reinforced felts and asphaltic materials had been developed. The asbestos felts were strong and durable and provided a measure of fire resistance. The asphaltic materials, by-products of the petroleum industry, were more advanced than the coal tar which had been commonly used. In the last 50 years the roofing industry became much more versatile and technical. In an effort to meet consumers' needs and in

response to the energy crisis of the 70s, several single ply membranes have been developed (Cram, 2002).

Today BURs are still the most popular industrial roof system in the roofing industry, but single membrane roofs are also used as viable alternatives. They have become more popular as labor and materials have become more expensive for asphalt BURs while the durability and flexibility of the polymers used to make the single ply membranes has improved (Laaly and Dutt, 2003) Depending on the type, single ply membranes can be applied in sheet or liquid form (Laaly and Dutt, 2003). Some of the popular single ply roofs include Ethylene Propylene Diene Terpolymer (EPDM), Poly Vinyl Chloride (PVC), and Thermoplastic Olefin (TPO) membranes. EPDM and TPO consist of sheets of rubber that are heat welded together to form one large membrane. PVC membranes are put together in a similar fashion. Hot applied liquid membranes are typically asphalt based compounds with rubbers or plastics added as plasticizers. The hot liquid is applied to a roof deck with a squeegee to form a seamless membrane that is typically about 4.5 mm thick (Laaly and Dutt, 2003). The cold-applied liquid membranes are a polymeric mixture of modified asphalt or coal tar pitch with resins and elastomers added. They can be applied as an emulsion or solution providing advantages over pre-fabricated membranes when used on irregularly shaped roofs (Laaly and Dutt, 2003).

2.4.2 Asphalt Built Up Roof

The conventional roofing that is normally installed on facilities at AFP4 is the asphalt BUR. Examples of the BURs are shown in Figures 2.1-2.3. Components in the BUR system include a roof deck, vapor retarder, insulation, membrane, and surfacing material (Scheirer, 2001). The membrane is made by applying alternating layers of asphalt-coated roofing felt or

fiberglass fabric and hot mopped tar. Each layer is considered to be one ply. A 3-ply roof is three layers of felt and tar, and the combination of the three layers would be considered the membrane. Above the layers of felt and tar, a thick flood coat of bitumen is applied. The flood coat adds to the quality of the membrane while holding the surfacing material in place. The surfacing material is usually gravel, which serves several purposes. The gravel layer gives the

Figure 2.1 Asphalt BUR. Roof drain and vent.

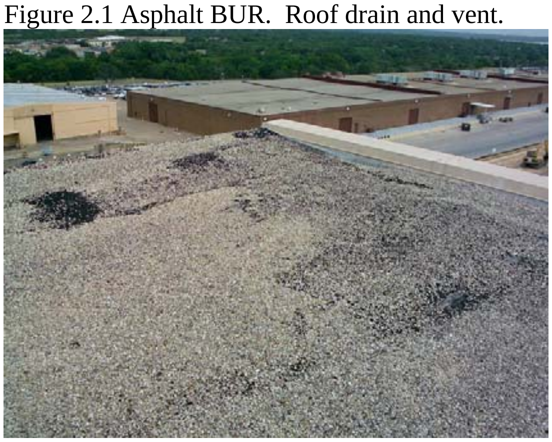


Figure 2.2 Asphalt BUR. Corner of Asphalt BUR and Building 15 in background.

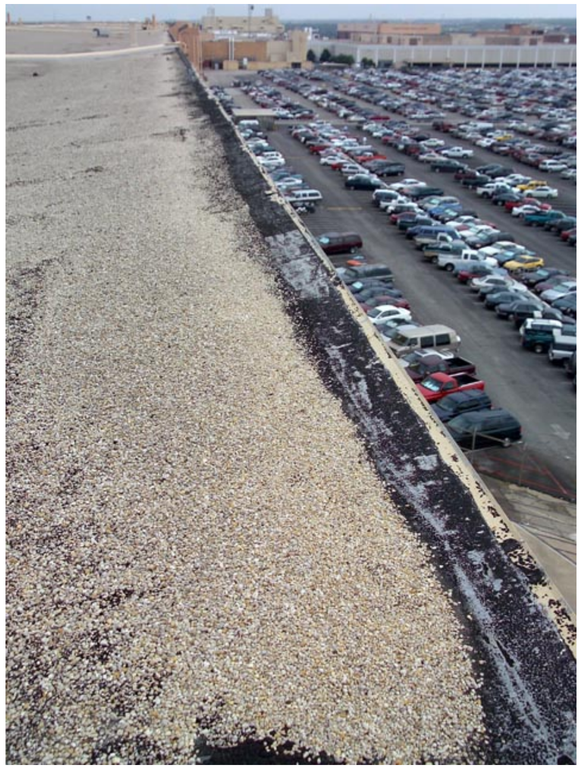


Figure 2.3 Impervious surfaces. Deteriorating BURs and large parking lots are one reason for considering vegetated roofing and its storm water retention capability.

roof a fire rating because the gravel will not burn. The gravel also holds the roofing material in place and offers some protection from damage by ultraviolet sunlight. Light-colored gravel used at AFP4 also reflects some of the sun's heat. Built-up roofs constructed in this manner typically last from 10 to 20 years, depending on the severity of the weather in the local area (Scheirer, 2003).

2.4.2.1 BUR Benefits

The asphalt BUR has several benefits. The asphalt BUR is the most popular industrial roofing system in the US. Since BUR has been around in its current form since the 1950s, the BUR industry is mature. There are many experienced contractors who can install this roofing system. Installation experience is important to getting a quality roof. Also, within the industry, heavy competition drives the installation costs down. Bids for the installation of asphalt BUR previously received in 2003 at AFP4 ranged from \$6.05 - \$7.60/ft^2 (Mockler, 2003).

2.4.2.2 BUR Disadvantages

When compared to other roofing systems, asphalt BURs have some disadvantages. Asphalt BURs typically fail due the degradation of the asphalt materials in the roof. The extreme temperatures on a rooftop cause thermal swings each day. These changes in temperature cause expansion and contraction of the membrane. The constantly changing stress causes the membrane to break down. Additionally, ultraviolet rays from the sun cause the membrane to degrade. Over time the membrane loses its flexibility and becomes brittle causing cracks. Because of this failure mode, BURs are replaced often. Depending on the climate, BURs need to be replaced every 10 – 20 years. The National Roofing Contractors Association has cited a study of over 25,000 roofs by Schneider and Keenan, performed from 1975 to 1996, that shows the average lifespan of an asphalt BUR is 13.6 years (Hoff, 2003). The lower installation cost of asphalt BURs is potentially negated over time because the system has to be replaced more often than other systems.

Additionally, materials from old asphalt BURs take up a lot of landfill space (Perry, 2003b). When the roofing systems are replaced, the cost and the environmental impacts of

disposal should be considered. The waste material that is removed from the roof is not recyclable and is typically placed in a landfill. Roof replacement efforts generate 6-8 pounds per square foot of material. Asphalt BURs typically have to be replaced every 10–20 years. Over the life of a facility, the roof material that must be disposed of can generate a significant cost for users and creates a burden on industrial landfills.

Maintenance costs add up over the course of the roof life as patches are needed often to fix leaks, especially toward the end of the roof life. Additionally, asphalt BURs typically have poor thermal qualities. Many times they are darker in color and absorb heat throughout the day. This absorbed heat contributes to higher energy costs to cool the building during summer months, contributes to urban heat island effect, and causes the roofing materials to break down (Scholz-Barth,2001:4; Dawson,2002; Perry, 2003b). Higher temperatures on roofs also contribute to smog because chemical reactions rates that create lower atmospheric ozone increase at higher temperatures (Chang, 2000:F2; Scholz-Barth, 2001:5). In general, asphalt BURs are not eco-friendly.

2.5 Vegetated Roofing

2.5.1 Introduction

In a world that has become more environmentally conscious, eco-friendly technologies that are economically feasible are being developed and implemented. One such technology that has been used in Europe and is gaining popularity in the US is the vegetated roof which is often referred to as a green roof. "Green" refers to the environmentally friendly qualities for which this roofing system is known, and not necessarily the color of the roof. With the multiple

environmental benefits that these roofs provide, a common perception is that green roofs are a new concept, but that is not the case.

Vegetated roofs have been in use for thousands of years, in one form or another. The hanging gardens of the Babylonian empire were well known for their beauty (Osmundson, 1999:112; Perry, 2003b). Necessity and a lack of other building materials brought about the sod roofs used by settlers of the American prairies (Osmundson, 1999:121; Sod, undated). The more technologically advanced green roofs in use today have been developed because of environmental concerns brought on by the disappearance of green spaces. Whatever the reason for building vegetated roofs, people have long enjoyed the beauty and effectiveness of plants on rooftops.

2.5.2 Components of a Green Roof

Vegetated roofs used today are more than soil and plants haphazardly placed on a rooftop. They are roofing systems with multiple components working together synergistically to provide long-lasting roof life coupled with environmentally-friendly and money-saving roof performance. The components of a vegetated roof, as shown in Figure 2.4, start with a waterproofing membrane placed on the roof deck. If the membrane does not have inherent root protection, a root protection barrier is applied to prevent roots from penetrating the water proofing membrane and causing leaks. Above the root barrier, a layer of rigid insulation can be added. Next, a drainage layer is put in place to remove excess water from the roof membrane when the plants and growing medium are saturated. A filter fabric is attached to the drainage layer to prevent soil and other particles from clogging the drainage layer. The growing medium, or substrate, is placed on the filter fabric. If the roof has a pitch of more than 20 degrees, a grid

or lath will be placed on top of the filter fabric. The lath prevents erosion of the substrate. The vegetation, usually sedums or grasses, can be planted by hydro-seeding, inserted as plugs, or placed as pre-grown vegetated mats. The multiple layers work together synergistically to provide longer roof life, increased cooling efficiency, improved water and air quality, and enhanced management of storm water.

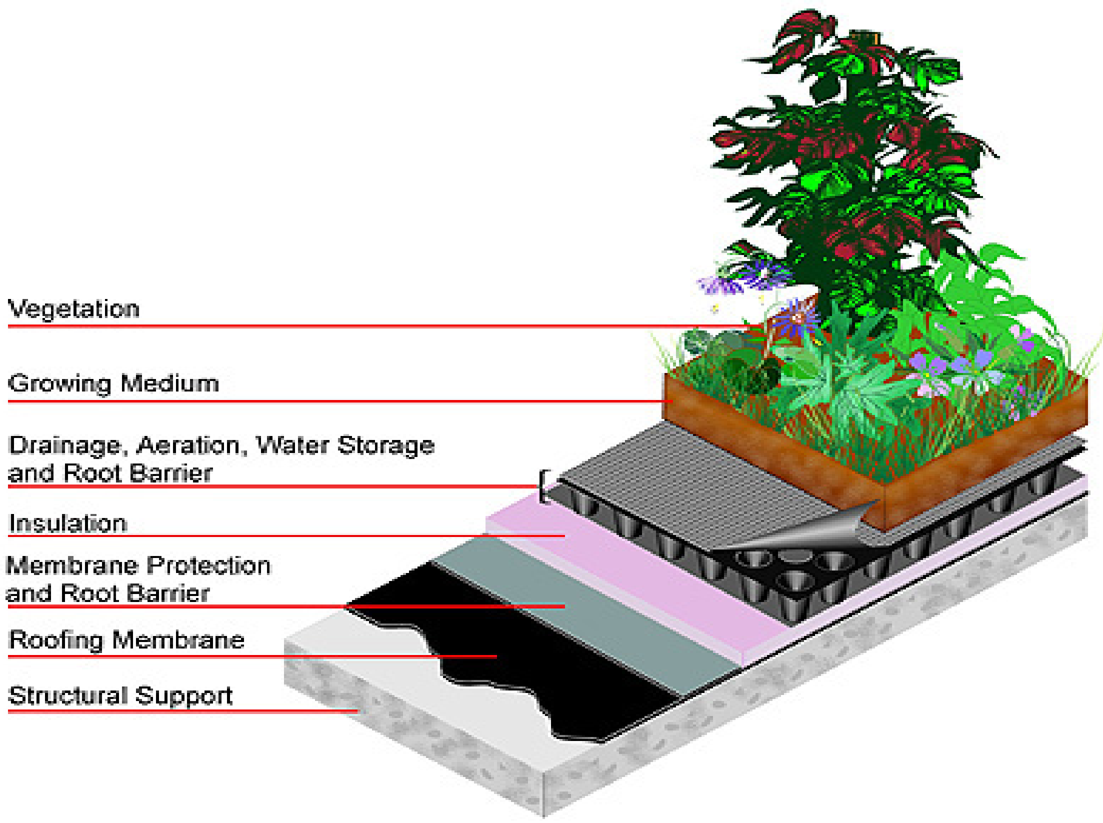


Figure 2.4 Green Roof Components (American Wick Drain Inc., 2003).

Waterproofing membranes have to be long lasting and durable. Replacing the roof membrane requires that all other green roof materials be removed from the roof. Therefore, special care must be taken when selecting the membrane. A quality membrane will meet Forschungsgesellschaft Landschaftsentwicklung Landschaftsbau e.V. (FLL) Standards (O'Brien,

2001:3). These are the only internationally recognized standards for green roof waterproofing membranes (O'Brien, 2001:3), although the American Society for Testing and Materials (ASTM) is currently drafting standards for the U.S. (Velasquez, 2003). There are several different types of membranes that can be used on green roofs. The most common materials used for waterproofing roofs are BURs, single-ply membranes, and fluid applied membranes (Osmundson, 1999:154,158)

Root protection can also come in several forms. In some cases the waterproofing membrane has inherent root protection. These membranes typically have a copper foil or copper powder that is incorporated into the membrane. In high enough concentrations, copper causes plant roots to stop growing or grow in a different direction (Haupt, 2003; Perry, 2003a). In Europe, chemical protection is sometimes used (Haupt, 2003; Perry, 2003a). Root resistant chemicals in the waterproofing membrane cause root growth to change direction away from the membrane. Protection boards are another form of root protection. They are typically placed on top of the waterproofing membrane. In addition to acting as a root barrier, protection boards prevent damage to the membrane during construction. Hard plastic panels have been used, and eight mm polyurethane film has also been effective in Europe (Osmundson, 1999:161).

The insulation that is most commonly used in vegetated roofs is polystyrene, or styrofoam. Polystyrene is an excellent material to use in green roof applications because it is lightweight, and easy to handle. Polystyrene typically comes in 4' x 8' panels that are easy to install, or they can be cut into the shape needed for the roof. The material is rigid enough to withstand the weight of the roof components above it.

Proper drainage is critical to the effectiveness of any green roof (Perry, 2003b). Excess water that is not removed from the roof can kill plants, can potentially stress the roof structure,

cause the waterproofing membrane to breakdown, and eventually penetrate the roof (Osmundson, 1999:164). Initially, modern green roofs used pebbles or broken rock for the drainage medium. However, these materials can add too much weight to some roofs and are labor intensive to install. In the 1970's hard plastics came into use as a drainage material (Osmundson, 1999:165). Plastics molded into attached cells looking like a large "honeycomb" worked very well. The plastic is strong enough to support the weight above it, and being below grade, ultraviolet rays do not break the material down. Similar applications are still used today.

Another draining mechanism is created by water-absorbing crystals. The water-absorbent gel crystals have been used as a water retention mechanism in horticulture applications for years (Perry, 2003a). These crystals actually serve two purposes in green roofs; they provide a water retention mechanism for the plants while simultaneously creating drainage paths. The German company, Famos, developed the waterproofing membrane that uses this technology, as seen in Figure 2.5. The membrane is manufactured with inherent root protection, water retention

Figure 2.5 Famogreen Ret. This water proofing membrane has inherent root protection and uses gel crystals to provide water retention capabilities.

capabilities, and drainage. Water-absorbing crystals are held in small square sections by a filter fabric material that is adhered to the membrane. As water drains through the growing medium and through the fabric material, the crystals absorb the water and expand until they are saturated. As the crystals expand, drainage paths are created allowing excess water to drain off of the roof. The water held by the crystals sustains the plants during dry periods (Haupt, 2003).

In applications where drainage mediums other than the water-absorbing crystals are used, a filter fabric is needed. The filter fabric prevents the growing medium and other debris from washing into and clogging the drainage layer. This filter material must be lightweight, rot-proof, and permanent (Osmundson, 1999:169). The material has to be porous enough to allow water to pass through while not allowing small debris to pass through. The most common material used resembles felt and is made of polypropylene fibers (Osmundson, 1999:169)

The growing mediums, placed on the filter fabric, are not just topsoil. The substrate is typically a blend of mineral rocks (i.e. perlite, lava rock, or shale), sand, and topsoil. The blend is normally about 60% mineral rocks, 25% sand, and 15% organic topsoil (Beattie, 2003). No more that 20% of the soil mix should be organic (Perry, 2003b). Only small amounts of organic soil are used because the organic components are broken down and consumed by the plants or dissolved in rainwater causing them to dissipate over time (Osmundson, 1999:170). If the growing medium started out as four inches of organic soil, within a few years only an inch of soil would remain. However, some organics are necessary in the substrate mix to help the plants establish themselves. Once the plants are established, they are capable of drawing nutrients from the mineral rocks. The main purpose of the sand in the soil blend is to facilitate drainage. The growing medium can not have many “fines” because they can clog the filter fabric and prevent excess water from draining off the roof.

Most plants on green roofs are selected because they do not have a lot of vertical growth and do not require mowing or trimming. The small amount of growth that is experienced during the plant's growing season typically dies and falls off during dormant periods. The portion that dies returns organic nutrients to the substrate as it decays – a sustainable process.

In some cases soil may not be necessary at all (Osmundson, 1999:170,179). Xeroflor, a green roof company based in Germany, performed tests in which little or no soil was present (Liesecke, 2003b). There were several variations to the tests, shown in Figure 2.6. Felt-like blankets impregnated with sedum seeds were placed on materials with different water-storing capabilities. In separate tests pre-cultivated vegetation mats (which had a small amount of soil held in place by the root system) were placed on the same materials. In some cases these seed-impregnated blankets were covered with a light-weight plastic mesh. This mesh held the mats in place, provided some shade for the sprouting seeds, and kept the seeds from blowing away or being eaten by birds. In other cases pebbles were placed on top of the seed-impregnated mats. The pebbles held the mats in place, provided some shade for the sprouting seeds, absorbed moisture that could be used by the seedlings, and kept the seeds from blowing away. The pre-cultivated vegetation mats did not have anything placed over them. The water-storing materials used in the experiments varied. They included a single course of aggregate, hygroscopic rockwool mats, slabs of modified foam, perforated water retention fleece, and Famogreen Ret (a waterproofing membrane with water retention capabilities). Within a short time the seeds sprouted and survived on the nutrients from fertilizer in the seed blanket and the moisture held by the water-retention materials under the seed mats. Sedums are hardy plants and can survive under extreme conditions. These test cases give an indication of their hardy qualities and their ability to grow without soil.

Figure 2.6 Soil-less plants. Xeroflor's seed-impregnated mats. Plastic mesh covers seed impregnated mats; pebbles cover others; pre-grown mats grow without soil as well.

Plant selection for green roofs depends to some degree on the climatic region where the roof is located. Factors such as rainfall, temperature, sunlight, wind, and maintenance requirements must be considered (Osmundson, 1999:146). Plants have to be able to withstand the extreme conditions that will be encountered on a rooftop. Typically, extensive green roofs contain mosses, succulents, herbaceous plants, and grasses (Liesecke, 2003a) Sedums, or stone crop, are the most common type of vegetation used on extensive roofs because they are the most drought-resistant and freeze resistant plants available (Perry, 2003b). Typically, multiple species of sedums will be placed on a roof so that when one species is dormant another may be in its growing season (Russell, 2003).

In some cases irrigation systems may be installed with a green roof. The need for irrigation depends on the climatic conditions of the roof location and the type of plants chosen for the roof. Irrigation can be applied with a drip system, an overhead spray system, or by an underground system with "pop-up" sprinkler heads (Osmundson, 1999:180). Each system has its

advantages and drawbacks. Care must be taken to ensure the irrigation system does not become a maintenance problem. Freezing temperatures can be a problem for systems installed in a shallow extensive green roof. Some irrigation systems utilize roof runoff water captured in containers and stored until it is needed; minimizing any burden on water supplies (Perry, 2003a).

2.5.3 Types of Green Roofs

There are two general types of green roofs. They are termed intensive and extensive. The major differences between the two types are the substrate depth and the type of plants. An intensive green roof greatly resembles a roof garden with large and small plants. Intensive roofs have at least six inches of soil depth, but typically require a minimum of one foot of soil to accommodate the plants they support. Small trees and shrubs as well as flowers and grasses can be planted on an intensive green roof. This type of green roof is much more costly to install than the extensive green roof. It is much more labor intensive and requires more materials than the extensive green roof. Also, the roof structure required for an intensive roof must be more robust to support the 80-150 lb/ft^2 of added weight that this system constitutes (Scholz-Barth, 2001:1). Intensive roofs are typically designed to be accessible and are usually meant to be enjoyed by the building inhabitants. These roofs do require a reasonable amount of maintenance and can be costly.

Extensive green roofs typically consist of a sedum or native grass surface that typically requires one to five inches of soil (Scholz-Barth:2001:3). This system creates a much smaller roof load than intensive roofs. Extensive roofs can weigh from 10-50 lb/ft^2 when the plants are mature and the roof saturated (Perry, 2003a; Scholz-Barth, 2001:1). Plants for these roofs are selected for their hardiness and ability to provide horizontal coverage. These species are not as

large, typically require little or no maintenance, and are cheaper to install and maintain. Extensive roofs are not designed for heavy foot traffic, although maintenance activities will not harm them. This type of green roof is built primarily for its economic and environmental benefits (Perry, 2003a; Scholz-Barth,2001:1).

2.5.4 Benefits of Green Roofs

Green roofs provide many ecological and financial benefits when compared to conventional roofs. Some benefits are easily noticeable, while others have a slow, positive, long term effect on the environment. Some of these qualities will be discussed below.

2.5.4.1 Longevity

Green roofs have the unique capability of prolonging life of the waterproofing membrane, the most important component of any roof. The multiple components on top of the membrane insulate the membrane from extreme temperature fluctuations. The dampening effect that green roofs provide from temperature swings reduces the amount of expansion and contraction that the membrane undergoes. The membrane still undergoes temperature fluctuations, but the temperature range is much less than an exposed membrane would experience, as shown in Figure 2.7.

Ultraviolet rays are the second major factor that shortens the life of a waterproofing membrane. The vegetation on the roof uses this sunlight for growth and prevents it from breaking down the membrane. The factors combine to lengthen the life of the roofing system. When installed properly, green roofs will last three times as long as an asphalt BUR (Perry,

2003a; Scholz-Barth, 2001:7). There are multiple examples in Germany where green roofs are performing without problems 30-60 years after installation (Osmundson, 1999:153).

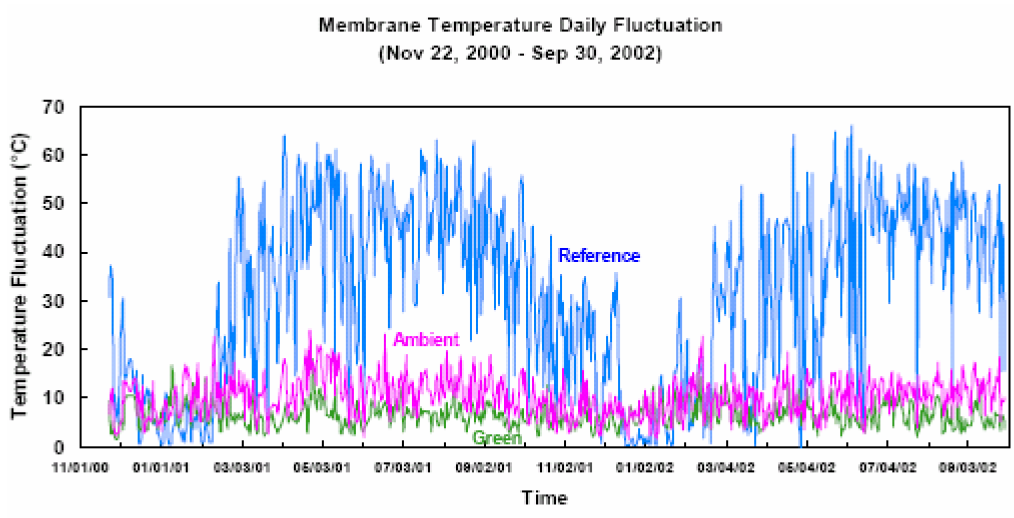


Figure 2.7 Temperature Measurements. Temperature measurements showed that the Green Roof significantly reduced the daily temperature fluctuation experienced by the roofing membrane. (Liu and Baskaran, 2003)

The waterproofing membrane is also preserved because it is protected from hail damage (Liu, 2003). Hail landing directly on an exposed membrane can do extensive damage. The impact of large hail stones can puncture the membrane causing leaks. The plants and substrate on a green roof acts as a buffer protecting the membrane from direct impact and the sudden change in temperature. Sedums and grasses are hardy enough that they would not be severely harmed by hail.

2.5.4.2 Thermal insulation

One of the most attractive aspects of a green roof, from an economic point of view, is the money that can be saved in cooling costs (Osmundson, 1999:28,31). Thermal savings vary depending on the way the green roof was designed as well as the local climate. In locations that are dry or only slightly moist, a green roof will on average provide an additional 25% insulating

effect (Scholz-Barth, 2001:4)). In wetter climates the insulating factor is negligible in the winter due to the water in the soil conducting heat (Scholz-Barth, 2001:4), but in dryer climates, some heating efficiencies are realized (Liu and Baskaran, 2003:4). However, in the summer the water has its benefits as the plants transform heat energy and soil moisture into humidity through evaporation and transpiration processes which have a cooling effect (Scholz-Barth, 2001:4). Also, vegetation provides shading that adds to this cooling feature (Liu, 2003). In areas where the temperature reaches 95^{o} F or higher, the cooling effect created by green roofs can be significant. With summer temperatures reaching such high extremes, traditional roof surfaces can reach 145–175^{o} F (Scholz-Barth, 2001:4; Liu, 2003) which affects the indoor and outdoor air quality. Green roofs can help prevent conditions like this by keeping the temperatures down. In one case, a 95^{o}F outdoor temperature resulted in a conventional roof surface reaching 158^{o}F while the membrane under a green roof was only 77^{o}F (Liu, 2003). On facilities with large roof areas covered by vegetation, this can result in significant savings in energy costs. For example, savings for Chicago's City Hall, which was retrofitted with a 21,700 ft^2 green roof, are expected to reach $4,000 annually (USAF, 2002:8). Various estimates for more moderate climates predict the potential to save anywhere from 10 - 30% because of reduced energy consumption (Dawson, 2002; Perry, 2003a). Green roofs are capable of reducing roof surface temperatures significantly. By reducing the roof temperature by 3-7 ^{o}F, air conditioning requirements can be reduced by 10% which has the potential to reduce cooling costs by up to 30% (Fedrizzi, 2003).

2.5.4.3 Storm Water

2.5.4.3.1 Storm Water Impacts

Storm water is generated by precipitation and runoff from land, pavements, building rooftops, and other impervious surfaces. Storm water runoff picks up and subsequently accumulates pollutants such as oil and grease, chemicals, nutrients, metals, and bacteria as it travels across land. Where storm sewers are tied into sanitary sewer systems, heavy precipitation or snowmelt can also cause sanitary sewer overflows which, in turn, may lead to contamination of water sources with untreated human and industrial waste, toxic materials, and other debris. EPA monitors and controls storm water and sewer overflow discharges through its National Pollutant Discharge Elimination System (NPDES). NPDES provides guidance to municipalities and state and federal permitting authorities on how to meet storm water pollution control goals as flexibly and cost-effectively as possible (U.S. EPA, 2003).

Our current methods of building design and massive urbanization contribute to storm water run-off. Some urban areas have vast amounts of impervious surface cover. Except for evaporation, any rain that falls on impervious surfaces becomes runoff. The force of gravity allows storm water to find its way through drainage systems to either a costly water treatment facility or to a body of water such as a stream, river, lake, or ocean. Studies show a direct link between runoff from impervious surface coverage and degradation of water quality in surrounding streams (Brown, 2001:4). Even relatively small amounts of runoff can lower water quality with inorganic, organic, and even thermal pollution. The temperature of water flowing across hot pavement will increase several degrees. As this water is dumped into a lake or stream, the higher temperature affects the oxygen level in the water. Additionally, storm water run-off pouring rapidly into storm sewers and then into streams cuts into stream banks causing erosion

and subsequent sedimentation. As water quality is degraded, the health of plants, animals, and ultimately humans can be affected.

In rural areas, rainstorms generate much less runoff than in urban areas. In rural areas, the majority of rain water is absorbed into the ground where it recharges aquifers and nourishes plants. For example, records indicate that parts of Pennsylvania receive 45 inches of average annual rainfall. In rural areas, only eight of those 45 inches become runoff (Bergstrom, 2002). In an urban area, the reverse was true – very little of the rainfall was absorbed. The remaining water became runoff and entered the storm sewer system.

There are several sustainable techniques for better management of storm water. The first technique is that of porous pavements that allow rainwater to enter the ground. Porous pavements may be a modified asphalt pavement made with open-graded course aggregate and asphalt cement or a specially formulated mixture of Portland cement and open-graded course aggregate (US EPA, 1999). Both types of pavements have enough voids to allow water to pass through. Asphalt porous pavement was installed at Walden Pond State Reservation in eastern Massachusetts in 1977. As of February 2002, the pavement still looked and worked well (Miller, 2002). This water, now allowed to drain instead of run off, recharges aquifers and is diverted from storm sewers. Secondly, urban sprawl and further destruction of green space can be avoided with proper planning. Instead of creating more impervious surfaces, city planners can develop incentives to encourage businesses to locate in areas already industrialized and where facilities already exist. Maybe the most obvious means to reduce storm water lies in green roofs. They are a cost effective and environmentally sound method to reduce storm water runoff.

2.5.4.3.2 Storm water retention

In urban areas most of the ground surface has been covered with buildings, roads, and parking lots. These structures prevent the rain from soaking into the ground, but green roofs can help manage storm water. The average green roof (construction and type vary considerably) will absorb 75% of the rain water that falls on it (Scholz-Barth, 2001:4). This water is absorbed into the soil layer and by the plants on the surface. The 25% of the water that does run off of the roof does so at a much slower rate, generally trickling out of the saturated growing medium of the roof. The peak runoff rate from a green roof can be reduced by 90% to one-tenth of what the flow rate would be from a conventional roofing system (Dawson, 2002). The slower rate of runoff decreases the need for large gutter and storm sewer systems, and the slower movement of the water decreases the number of particulates that the water can collect en route to a storm drain.

The amount of water retention varies greatly from roof to roof and depends on many factors like substrate depth and type, rain intensity, type of vegetation, time between rainfall events, seasonal weather, roof pitch, and orientation to the sun. The components of the roof may be the biggest factor. The level of water retention can be increased by adding a layer of mineral wool, or recycled foam, or even installing a membrane that has water-absorbing crystals built-in.

Adding more water retention components is done for the health of the plants. Water retention is important in climates that have high temperatures or long periods with little rainfall. Different plants have differing retention capacities. Grasses and mosses retain some water, but sedums retain much more. Sedums function like cacti. When a rain comes, they take in as much water as possible and store it.

Roof characteristics are another factor in water retention. Higher pitched roofs shed more water than roofs with a slight pitch, especially in higher intensity rains (Rowe, 2003:7-9). During less intense rains much of the water soaks into the substrate, but during heavy rains more of the water runs off of the roof (Rowe, 2003:4). Orientation to the sun is factor in water retention. Being in the Northern Hemisphere, much of the sun exposure comes from a southerly direction. Southern facing roofs dry out quicker than roofs facing north. Therefore, a roof on the south side of a building typically retains more rainfall than the north side of the roof (Behrens, 2003). Time between rainfall events is another crucial factor (Hutchinson et al., 2003:9,11). If rain showers are close together in time, a green roof may still be saturated from the first rain when the second occurs. Being saturated, the excess water would sheet off the roof (Russell, 2003). Seasons are closely tied to temperatures and wind conditions which play a large role in the rate at which a green roof dries out. In Portland, Oregon, almost 100% of summer rain landing on green roofs is absorbed. However, in cooler fall temperatures, the roofs may only retain 40-50% of the rain. The retention level may drop to 10-20% in the winter (Dawson, 2002).

Water retention levels vary from roof to roof. No two green roofs are exactly alike. The depth and the maturity of the plants make a considerable difference in water retention. On average, one inch of sedum over a two inch deep gravel bed will retain 58% of the rainfall that it receives. Sedums and grasses that are 2.5 inches in depth over the two inch gravel bed retain 67% of the rainfall, and four inches of sedums and grasses will retain 71% (Scholz-Barth, 2001:4). Retention levels this high are exceptional when considering that the plants are growing on a gravel bed. Substrate mixes can be designed with higher water retention capabilities than gravel. In a two inch rainstorm, approximately 1.25 gallons/ft^2 of water will land on a roof.

Forty percent, or 0.5 gallons/ft^2, of this volume could be retained by an extensive green roof that is 2.5 inches thick (Scholz-Barth, 2001: 4).

The water retention properties of green roofs can save users money through construction grants, by reducing tax dollars spent on storm sewers, and tax exemptions for pollution prevention. Grants are available for green roof construction through the EPA's Clean Water Act Section 319 grant program (U.S. EPA, 2003a:). The program is designed so states can provide funds when non-point source pollution control is needed to maintain water quality standards on a navigable body of water. Green roofs prevent pollutants from being carried to bodies of water by reducing runoff volumes. Decreasing the volume of runoff also reduces the required size of storm sewers. Smaller storm sewers cost less money, which ultimately reduces tax dollars spent to manage storm water. In Germany property owners are assessed a rain tax. The tax is based on the amount of impervious surface cover that contributes to storm water volumes. Green roofs allow property owners to be exempt from a portion of these taxes (Scholz-Barth, 2001:7).

2.5.4.4 Improved Microclimate

Green roofs improve air and water quality. Particulates are removed from the air by the vegetation. As particulates blow by the plants, they are intercepted and adhere to the leafy structure of the plants (Temple, 2003). There can be three to four times as much dust in the air in non-vegetated areas with 10,000 – 12,000 dust particles per liter of air compared to only 1,000 – 3000 dust particles per liter of air in vegetated areas (Temple, 2003). Rain washes the dust from the leaves and it becomes part of the growing substrate. As plants conduct photosynthesis, they consume carbon dioxide, and release oxygen. A 1.5 square meter section of uncut roof grass could provide the annual oxygen requirement for one human (USAF, 2002:10; Cardinal, 2003).

The ability of green roofs to prevent roof surfaces from reaching extreme temperatures improves smog conditions. Higher temperatures increase the chemical reaction rates that produce lower atmospheric ozone, a major component in smog (Chang, 2000:F2; Scholz-Barth, 2001:5). Water quality is also improved in several ways. Green roofs act as a filter to rain water. As the water goes through the substrate to reach the drainage layer of the roof, the substrate cleans the water through filtration mechanisms and also bacterial action (Scholz-Barth, 2001:3). As mentioned previously, streams and rivers are healthier because green roofs reduce storm water runoff that deposits chemical and thermal pollution in these bodies of water.

2.5.4.5 Urban Heat Island Effect Reduction

In large cities, summertime temperatures can be as much as 10 – 12 ^{o}F hotter than surrounding rural areas (Osmundson, 1999:29; Perry, 2003b). This difference in temperature is due to the urban heat island effect (UHIE). This occurs because darker rooftops, streets, parking lots, among other things absorb solar energy and re-radiate it as heat (Dawson, 2002) It is not uncommon for rooftops to reach temperatures greater than 140 ^{o}F during the summer (Perry, 2003a; Scholz-Barth, 2001). The cumulative effect is warmer ambient air temperatures around those dark surfaces, increasing cooling demands which translate into greater energy use. Air conditioners compound the situation by emitting hot exhaust. The energy used for air conditioning is typically generated using fossil fuels.   This, in turn, creates more greenhouse gases and contributes to smog. UHIE initiates an unhealthy, environmentally-damaging cycle.

Green roofs help combat UHIE. They prevent rooftops from reaching extreme temperatures by providing shade to the actual roof membrane and through evapo-transpiration. In the summer, Chicago City Hall's roof is usually 25 to 80 ^{o}F cooler than the adjoining County

building's roof which has a conventional roofing system (Dawson, 2002). The vegetation transforms the solar energy and carbon dioxide into oxygen and plant tissue. A recent study by the Lawrence Berkeley Laboratory showed that a mere 5% increase in green space in a large metropolitan area would reduce the average summertime temperature by 4 ^{o}F, and would reduce smog by 10% (Perry, 2003b). These kinds of statistics are inducing cities and the federal government to begin mandating or providing incentives for the use of green roofs (Perry, 2003b). Environment Canada did a study that indicated if only 6% of the roof area in Toronto was covered with green roofing, greenhouse gas emissions could be reduced by 2.4 megatons/yr (Dawson, 2002).

2.5.4.6 Acoustics

Green roofs provide acoustical benefits because of the dampening effect of the roof system (USAF, 2002:10). The overall mass on the roof tends to absorb sound waves emitted overhead and in the surrounding area. The thickness of the substrate layer and the density of the plant growth play a large role in how much sound the roof can absorb. Vegetated roofs have been placed on airports and facilities in line with flight paths. Specifically, improvements were noted in interior noise levels at the Gap headquarters building in San Bruno, CA (Burke, 2003:3). Tests have shown that green roofs can reduce the amount of exterior noise heard by building occupants by up to 40 decibels (Fedrizzi, 2003).

2.5.4.7 Aesthetics

A qualitative benefit of vegetated roofs whose significance should not be overlooked is improved aesthetics. The appealing view facilities users notice is not insignificant. Green roofs are aesthetically pleasing. Roofscapes are enhanced green roofs. Studies have shown that worker morale and productivity have improved when they have access to a view of a lower level green roof (Burton, 2003). There have been indications that hospital patients heal faster when they have a view of a green roof as opposed to a lower level asphalt roof (Perry, 2003a). A dollar value for aesthetics can be hard to assess, but not in all cases. Property value could be potentially increased while hotel managers could charge more for rooms overlooking a green roof (Osmundson, 1999:27). Even if no value is gained monetarily, green roofs are appealing to the eye.

2.5.4.8 Animal Habitat

Urban development destroys wildlife habitat. Each year in the US, thousands of acres of green space are lost to new development. Animals are driven to other areas to live. Green roofs help combat this problem by providing green space in urban areas. Birds are the most obvious benefactors. Many birds that nest on the ground will nest on green roofs. The vegetation attracts the birds. Being on the roof, the nests are more protected than they would be in a field on the ground. While there is no formal quantifiable measure that shows when an area is eco-friendly, the presence of songbirds is considered to be a good indicator of a healthy environment. Birds were seen nesting on Ford's River Rouge manufacturing plant green roof before it was a year old (Russell, 2003).

2.5.4.9 State and Federal Funding

Because green roofs are so environmentally friendly and prevent pollution in multiple ways there are several avenues to receive funding grants to help defray installation costs. The EPA Clean Water Act Section 319 is a grant program on the state level. If state approval is given, users can be given grants for construction if the roof prevents pollution from reaching a navigable body of water where required standards are not being attained or maintained (US EPA, 2003). There are many other potential avenues for funding. Some pollution prevention programs could easily apply to green roofs because they fulfill the purpose of the programs. In Illinois, property taxes are reduced when land owners develop vegetated filter strips (Scholz-Barth, 2001:7). The Illinois program was set up to encourage land owners to install these strips which are known to reduce erosion, filter and retain water, and provide animal habitat. Green roofs function in a similar fashion, and the law could be adapted so that green roofs could be considered for the same tax reduction. Power utility companies could find ways to offer incentives to users who reduce energy use during peak demand. Green roofs reduce energy demands during summer months.

2.5.5 Disadvantages of Green Roofs

2.5.5.1 Costs

For all of the benefits vegetated roofing systems offer, there are some disadvantages to this type of roofing. The primary disadvantage is the initial cost of a green roof. With past green roof projects in the US, it was common for installation costs to be almost twice that of conventional roofing systems (Scholz-Barth, 2001:6). This higher up front cost is due to the additional components that are necessary to support plant life on the roof such as the root barrier,

drainage, water retention, growing medium, and plants. As the industry is developing, those costs are decreasing. Depending on the area and size of the roof, installation costs for green roofs can be within 20 - 30% of conventional systems (Perry, 2003a). While the cost of a green roof may be more than conventional roofing, overall facility construction costs may be reduced. Green roofs can reduce the summer cooling loads allowing air conditioning equipment to be downsized. It is not unreasonable to expect overall new construction costs to be very close to facility costs that include conventional roofing systems (Lierly, 2003).

2.5.5.2 Structural Support

With new construction, the additional weight of a green roofing system can be accounted for in the facility design, but retrofits can be more difficult. Most facilities have the structural capacity to support a green roof, but if not, adding a green roof can be a costly inconvenience. Before green roofs are installed on existing facilities, structural analyses are needed. If the support structure needs additional strength, adding that support can be difficult. This added difficulty and cost may dissuade users from using a green roof. However, most roof structures are more than adequate. Extensive green roofs can weigh as little as 4 – 6 lb/ft^2 more than conventional systems.

2.5.5.3 Initial Maintenance

Another disadvantage associated with green roofs is that of maintenance. In arid climates irrigation and care are needed for the first six months to two years after the roof system is installed. The amount of care depends on the type of green roof installed. During this time,

plants are able to establish themselves. After the plants mature, much less irrigation and maintenance are needed.

Frequent irrigation and deeper substrate depths allow weeds to grow. Weeds typically flourish in moist conditions. Weeds will not provide the same roofing performance that sedums are proven to provide. Herbicides could be used to combat the weeds, but that is contradictory to good environmental management. Weeding by hand can be labor intensive but may be necessary to maintain a quality roof until the preferred plants are mature enough to prevent weeds from growing.

Some green roofs require an annual application of fertilizer. This is not necessary in most cases, but some roofs need the additional nutrients to remain healthy and vibrant much like typical lawns and other fertilized areas on the ground. Runoff from these roofs is likely to have higher levels of nitrogen and phosphorus. These elements have the potential to be harmful to the streams and lakes that they reach negating some of the benefit of the green roof.

2.5.5.4 Leaks

Another perceived potential problem with green roofs is the prospect of leaks. Unless the waterproofing membrane adheres tightly to the roof, water can migrate making leaks difficult to locate. Large portions of a roof garden may have to be removed to find leaks making them costly and difficult to repair (Osmundson, 1999:157). However, with proper installation and improved technology in the manufacture of the waterproofing membranes, leaks are rarely a problem (Scholz-Barth, 2001:6). Adequate membranes must be chosen. Only high quality membranes that meet the German FLL standards are used in green roof applications. In the 1970’s there was a push for energy efficient building practices. Some of the buildings

constructed during that time had sod roofs. Many of these roofs were poorly constructed, and leaks were a problem on those facilities (Scholz-Barth, 2001:5). However, if care is taken when the waterproofing layer of a green roof is installed, leaks can be avoided (Scholz-Barth, 2001:5).

2.5.5.5 Infant Industry

The vegetated roofing industry is a new and developing industry in the US. While the industry is maturing, there are some growing pains that must be endured. In this country there are fewer experienced contractors who can install green roofing than other types of roofing. Plants needed for the vegetated roofing systems are not always readily available. With a limited number of roofs in each region of the US, roof performance data is limited. These issues can be overcome, but they must be addressed when considering the installation of a green roof (Perry, 2003a).

There are not a lot of experienced green roof providers in the US compared to the number of available asphalt BUR contractors. One green roof contractor may have to service an entire region of the country. As the industry develops, more contractors will install green roofs which will provide more competition, most likely drive costs down, and improve quality. Because there are not many green roof contractors, there are few workers in the US with experience installing this type of roof. Experience helps workers properly install the system. Without proper installation of the components in a green roofing system, the roof performance suffers.

One of the critical components in a green roof is the vegetation. Because of the newness of this industry in the US, there has not been a large industrial demand for sedums and other plants typically used on vegetated roofs. As the industry develops and the demand for the necessary plants increases, plants will be grown in advance. Currently, plants are not readily

available for large jobs. In recent applications, plants have been grown for specific green roof projects. In Europe, mats are grown in advance, much the way sod is grown in the US. When a large green roof is being installed, contractors have access to pre-grown mats, plugs, or plant cuttings.

Cost withstanding, vegetated mats are considered the optimum way to install the vegetation, as opposed to plugs, clippings, or hydro-seeding. The plants in the mats should provide at least 70% surface coverage before the mats are harvested and installed on a roof (Russell, 2003; Xeroflor, 2003). Growing the vegetated mats to this level of maturity takes time and is the most expensive method for developing roof cover. However, when mats are installed, the roof is functional immediately. Mats require less initial maintenance than other installation methods. When the vegetation is installed as plugs, clippings, or by seeding, the roof has to be monitored more closely until the plants establish themselves.

Because there are not many green roofs in the US, documented roof performance data is limited. There are several factors that contribute to the shortage of information. First, the US is such a large country that the climate varies throughout. A green roof that works well in one location may have to be modified to work satisfactorily in another. The variance in the roofs makes it difficult to derive specifics about green roof performance. The second factor that contributes to the shortage of information is the newness of green roofs in the US. Vegetated roofs, in their current form, have not been in existence long enough to collect long-term data. The assumptions and generalities about green roofs are based mainly on the performance data collected from roofs in Europe.

2.6 Related Legislation

In the US there is legislation to preserve natural resources and to promote environmentally friendly practices. The legislation ranges from executive orders issued by the president of the US to local laws acting as guidelines for small town municipalities and farms. Green roofs allow facility users to comply with many of the requirements outlined in these laws.

Executive Order 13148 - Greening the Government Through Leadership in Environmental Management - signed into law in April 2000, specifically addresses incorporating environmental accountability into day-to-day operations and long term planning. The order outlines several ways this should be done. Section 302 states that federal agencies are to establish programs to implement life cycle assessments and environmental cost accounting principles in their activities. The order addresses environmentally and economically beneficial landscaping used to reduce adverse impacts to the natural environment. Federal agencies are directed to emphasize pollution prevention as a means to achieve and maintain environmental compliance. These things are to be done by developing and implementing environmental management systems that ensure work strategies support environmental leadership programs, policies, and procedures (US EPA, 2000). Green roofs potentially allow users to meet each of the requirements mentioned above.

Executive Order 13123 - Greening the Government Through Efficient Energy Management - addresses environmental concerns by focusing on improving energy management within the federal government to save the taxpayer dollars and reduce air emissions that cause pollution and global climate change (FEMP, 1999). The preamble to the order states that the federal government is the nation’s largest energy consumer and has over 500,000 buildings (FEMP, 1999). A reduction in energy consumption throughout the federal government would

save millions of dollars and significantly reduce air emissions. Implementing green roof technology is a potentially viable means to realize these benefits. Green roofs can reduce energy consumption by 5-25% depending on the location, climate, and type of green roof (Perry, 2003a; Dawson, 2002).

Green roofs help users achieve or maintain compliance with non-point source discharge (NPSD) and the National Pollutant Discharge Elimination System (NPDES). The NPSD falls under many different forms of legislation that governs areas ranging from agriculture to seepage from soil-based wastewater disposal (NCSU, 2003). Non-point source pollution is water pollution not associated with a distinct discharge source (NCSU, 2003). Most non-point source pollution comes from storm water runoff that drains from roads, parking lots, farms, etc. directly into a body of surface water. The water retention capabilities of green roofs could greatly reduce this type of water pollution, at least in urban areas.

Storm sewer systems often deposit storm water runoff directly into a body of surface water via a specific outfall. The specific outfall would be a point source for water pollution. NPDES regulates point source pollution. The Clean Water Act authorized NPDES in 1972. NPDES is a national program that is run by each state. States use a permitting system to allow entities to discharge tolerable levels of pollution into streams and lakes. States are responsible for ensuring that the total discharge does not exceed pollution standards. Green roofs might prevent large volumes of storm water from reaching storm sewers enhancing the ability of municipalities to meet NPDES standards.

In Germany, legislation affects green roofs in several ways. The country has responded actively to the disappearance of green space. In most parts of the country, commercial developments are required to install green roofs (Scholz-Barth, 2001:7) to replace developed

green space. In Hamburg, Germany, at least 75% of the green space that is developed has to be replaced. Developers have the option of installing a green roof or developing brownfield sites (USAF, 2002:6). In residential areas many houses have vegetated roofs. Carports and garages have green roofs as well. One reason there are many green roofs is the exemption the roofs offer from "rain taxes." Homeowners are taxed on the amount of impervious surface cover on the property that creates runoff and contributes to the storm sewer discharge (Scholz-Barth, 2001:7). The German government recognizes the water retention qualities of green roofs and provides the incentives for citizens to use green roofs.

Green roofs are a unique, innovative way to incorporate positive economic and environmental impacts into the roofing industry. This unique roofing system incorporates sustainable principles in a way that benefits users and the environment. A paradigm shift in the roofing industry may be necessary before the vegetated roof will become as widely used as its chief rival, the asphalt BUR. However, when the benefits of its use are compared to the disadvantages, vegetated roofs appear to be an excellent roofing system.

III. METHODOLOGY

3.1 Introduction

Green roofing technology is relatively new to the U.S., and information about this technology is somewhat limited. Because of this dearth of information, the case study method was chosen as a means for collecting information about individual roofing systems. This method allows the investigation of current cases where the technology has been fully or partially implemented and the collection of data for application to future cases. After gathering data on multiple cases, the information obtained influenced the design of a green roof for Building 15 at AFP4. After a cost estimate was developed, the economic portion of a life cycle analysis was performed so the green roof could be compared to the conventional roofing system that would typically be installed on this facility. This comparison along with information gathered in the case studies and other literature research will allow decision makers to determine which roofing system is most feasible for Building 15.

3.2 Case Studies

Case studies are one of many valid ways to perform research. Many times case studies are used when there is little documented data on a topic. They also lend themselves to research that is determining “how” or “why” a phenomenon happens (Yin, 1994:1). This research effort meets these criteria. An effort is being made to determine how a green roof compares to a conventional asphalt built up roof (BUR). Determining the ways a green roof may be better than a BUR will help the AF determine whether or not to implement green roof technology. Determining why a green roof is better will allow AF designers to maximize those properties to

obtain optimum roof performance. In order to answer the “how” and “why” questions, an exploratory case study was performed.

The intent of the case study was to collect data on multiple green roofs and note similarities and differences between them. In essence, the study determined which applications were most successful and which were least successful. In order to note these similarities and differences, the questions that were asked in these case studies were formulated in a manner that would simplify the assimilation and comparison of the answers. The questions were based on the rationale that the keys to a successful green roof would be found in the roofing materials and application methods used in the installation. The data collected and the additional comments from green roof users and experts would confirm or disprove this initial assumption.

There are three criteria for judging the quality of an exploratory case study research design – construct validity, external validity, and reliability (Yin, 1994:33). Construct validity is shown by using multiple sources of information and having informants/experts review the data that has been collected. Data was collected on eleven different cases, and experts familiar with each roof verified the collected data was accurate. External validity is seen when the findings from multiple case studies can be generalized. The same type of data was collected on each roof allowing generalizations to be made about the green roofing systems. Reliability is noted when similar results are produced by using the same procedures in multiple case studies. The same procedures were used in each case study generating similar types of results for each roof. However, portions of data were unavailable for some roofs. This investigation met each of the criteria for a quality case study design.

Besides a quality case study design, another key to successful data collection is flexibility. The questions were formulated to ensure that specific information was requested.

However, if the answers to the questions were not accessible or readily available, the researcher was able to adjust and gather any relevant data that was available.

Case study evidence comes from six types of sources (Yin, 1994:78). These sources include documents, archival records, interviews, direct observation, participant observation, and physical artifacts. Five of the six types of sources for collecting information were used during the data collection phase of the current case studies. Multiple documents from books and the internet were cited. Archival records were provided by three green roof companies. Data collection was conducted with company presidents, contractors, university professors, and facility users. Multiple roofs were observed after installation, and one installation was observed in progress. The tools and materials used in the installations were examined closely to see how they worked. The only information gathering technique not used by the researcher was active participation in green roof construction or maintenance activities. Gathering data by five of six means gives a well-rounded perspective about the intricacies of green roofs. Data were collected using the forms found in Appendix A.

Once collected, the data were arranged in a tabular format as shown in Table 4.1. This arrangement lends itself to simple comparisons between the roofing systems. One can see the list of characteristics of each green roof and distinguish similarities and differences.

The cases from the U.S. that were observed during this investigation were chosen for their significance. They are some of the largest and most well-known green roofs in the country. The Ford roof is considered the largest vegetated roof in the world right now (454,000 ft^2). The Chicago City Hall roof is well-known because of the city government's endorsement of green roof technology and the city's effort to encourage the technology's implementation throughout the local area. The success of the roofs has a measure of national significance because they are

so well-known. People and organizations around the country are watching to see how successful these roofs are before implementing the technology on their facilities.

3.3 Life Cycle Assessment

A life cycle assessment (LCA) is a means of looking at the effects associated with any given activity from the collection of raw material to the point at which all residuals are returned to the earth (Bishop, 2000:252). An LCA involves a holistic approach. This type of evaluation is able to give an accurate depiction of the true impacts and costs that an activity creates. To address all impacts of a process, LCAs typically have, as a minimum, the following four stages: goal setting, inventory analysis, impact assessment, and improvement analysis. The assessment addresses more than the energy used and the emissions generated during just the manufacture and use of a product. The impacts on the environment cover a broader spectrum. When the entire process is addressed, the effects of indirect impacts are assessed and often far outweigh the effects of direct impacts. In a cursory look at a process that does not involve a LCA, many harmful effects are often overlooked.

LCAs are performed for several reasons. They can be used for process improvement, product development, evaluation and comparison of products, and corporate strategic planning. An LCA will frequently involve a life cycle economic assessment, also.

3.4 Life Cycle Economic Assessment

The assessment used in this process will be only one component of a full LCA, the life cycle economic assessment (LCEA). For this effort it was not practical to measure all impacts created from raw material extraction to material disposal for the green roof system. To perform

a full LCA would require more time and money than that allotted for this research effort. A full-scale LCA can have costs ranging from $10,000 to several hundred thousand dollars (Bishop, 2000:269). A useful evaluation for this thesis can be conducted without going into such great depth. Life cycle cost will be the most critical factor used in determining feasibility of a green roof at Building 15.

LCEAs involve recording more that just installation costs. There are other factors to consider besides the labor and material used to build a roof. These other factors, such as maintenance, are considered life cycle costs. Green roofs contribute to savings in several ways and this must be recorded in the cost analysis. One way savings are realized is a reduction in energy consumption that results from the cooling effects of green roofs. Ambient air temperatures in the space just above green roofs are cooler than the air above conventional roofs (Osmundson, 1999:31; Perry, 2003a). Air conditioning equipment does not have to work as hard to cool the air that is being used to cool the facility. Green roofs also reduce the amount of heat transferred into a facility through the roof (Liu, 2003; Osmundson, 1999:31). Therefore, the need for air conditioning is typically reduced. Reduced temperatures on a green roof are also likely to increase the longevity of air conditioning equipment (Perry, 2003a). These are examples of reduced life cycle costs that would be used in the LCEA.

The goal of the LCEA is to provide decision makers with precise information that will allow them to make an informed decision concerning the most feasible roofing system for Building 15 at AFP4. For this evaluation, the life cycle costs of the roof will be broken down into an easy-to-follow format for an extensive vegetated roof and for a conventional asphalt BUR. The environmental benefits that lend themselves to a determinable cost will be included in

the comparison. Qualitative benefits that cannot be assigned a specific dollar value will be discussed, but will not be a formal part of the cost analysis.

Economic impacts considered during LCAs can extend from cradle to cradle. Assessing costs over the entire life cycle of the roofing project is not feasible for this research effort. This assessment will range from the point of product acquisition to the end of the life cycle for the roofing systems. By establishing clear and concise boundaries, the comparisons can be more accurately assessed. Costs that will be addressed include: removal and disposal of current roof, installation of the new roof, maintenance, and energy savings derived from the roofing system. Cash flow diagrams will graphically illustrate monetary disbursements and savings over the life cycle being evaluated for each roofing system. The values shown in the cash flow diagram will be used in a calculation that will show the net present value (NPV) of all costs over the life of each roofing system. These calculations will allow decision makers to easily compare the conventional roofing system with vegetated roofing. In the cash flow diagrams, disbursements will be shown with an arrow pointing downward. Funding offsets or monetary savings will be shown with arrows pointing upward. This illustration gives a concise picture of monetary actions over the life of the roofing system. Figure 3.1 is an example of what a cash flow diagram may look like.

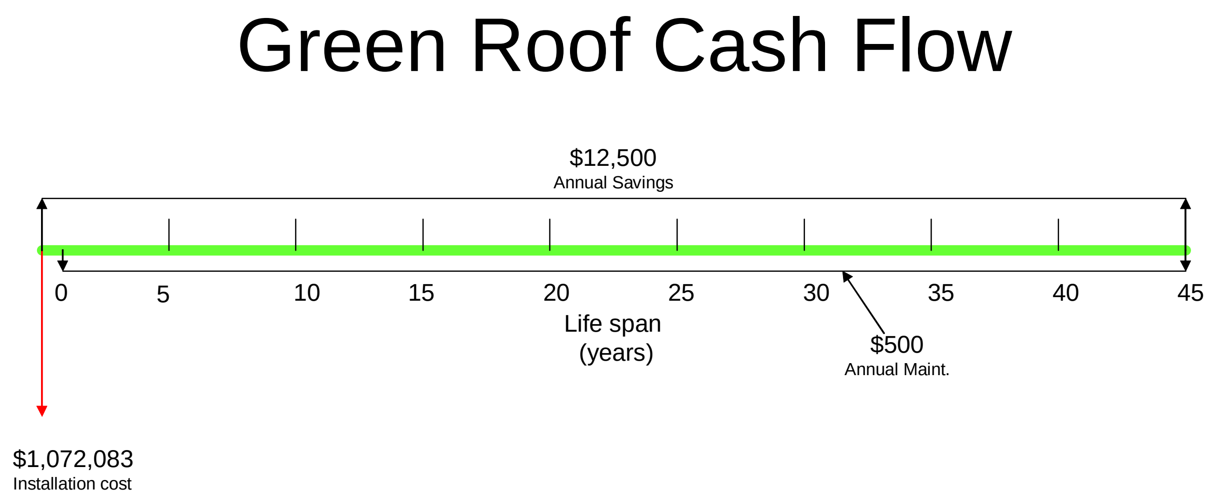


Figure 3.1 Cash Flow Diagram - an example of a cash flow diagram that will be used in the LCEA.

The NPV is a tool that allows decision makers to compare two or more alternatives on an economic plane (Fabrycky, 1991:39). NPV brings all costs over the life of the roofing system to a present dollar value (Fabrycky, 1991:53,55). Future dollars spent or saved will be worth less than their present value because of the effects of inflation. If costs used in this evaluation are in future values, inflation will be accounted for by incorporating an inflation rate in the calculations. An appropriate inflation rate will be obtained by determining the long term trends of the United States' consumer price index (CPI). The NPV is the sum of the annual costs for each year during the life of the roof divided by the compounded interest rate. If all life cycle costs are in present day values, the costs can simply be added without accounting for inflation. The equation that incorporates inflation is shown in Equation 3.1.

$$NPV := \sum_{n=0}^{N} \left[\frac{AnnualCosts}{(1+i)^{n}} \right] \qquad (3.1)$$

i = annual rate of inflation

n = single year in a series of N years in the roof's life cycle

N = total number of years in the life cycle

3.5 Procedures

To effectively compare a vegetated roofing system with a conventional asphalt BUR at Building 15, the best type of vegetated roof for that facility had to be determined. With the limited amount of documentation on the performance of vegetated roofs in the U.S., up to date information was sought. In order to gain knowledge in this new field, green roofing experts were consulted, and case studies were performed on pre-existing roofs in the U.S. Since there are no known vegetated roofs in the U.S. that have been in existence for an extended period of time, case studies were performed in Germany as well. There are green roofs in Germany that have been in place for as long as 60 years. The collected data was compiled to aid in determining which roof design would provide the best overall performance on Building 15.

Several green roofs in the US were identified so that analysis of the systems could be initiated. Chicago City Hall and Ford Motor Company's new River Rouge manufacturing facility in Dearborn, Michigan were chosen for the case studies. A list of questions, shown in Appendix A, was developed to facilitate gathering information about the various components and the overall performance of the roofs. The same list of questions was used for each roof so that the same type of information could be gathered.

In order to gain long-term performance data, case studies were performed on roofs in Germany. Many roofs were observed with varying amounts of information available on each one. These roofs were much older, and more performance data was available. These cases also provided a different perspective on construction techniques and environmental issues.

A visit to AFP4 was necessary to gain a better understanding of the conditions in which the green roof will be installed. Lockheed Martin (LM) personnel provided access to the rooftop for a visual inspection. In an effort to gather relevant information about Building 15, a prepared list of questions was given to LM's facilities engineers. That form is shown in Appendix A. The engineers assembled the answers to the questions and returned the information electronically. LM personnel also supplied roofing plans for the current asphalt BUR as well as pictures of the rooftop.

Michael D. Perry, president of Building Logics in Virginia Beach, Virginia, developed a preliminary design of a green roof for Building 15 in order to develop a cost estimate for a new roofing system. The cost estimate included disposal of the current roofing system, labor and materials to install the green roof, and the initial maintenance necessary to ensure vegetation was properly established. This cost estimate was the basis for the installation cost of the green roof in the LCEA, and is shown in Appendix B.

Other costs that were included in the economic comparison were long-term maintenance costs and annual energy savings realized over the roof's useful life. An Excel spreadsheet was used to prepare the LCEA. After the costs were placed in the spreadsheet, a NPV was calculated. Explanations were given for any predicted values, such as expected energy savings, that were used. The spreadsheet was set up to allow these numbers to be adjusted to higher or lower values based on any future insights or estimates. Therefore, a range of NPVs was

established based on potential savings or costs. Three specific values were calculated – a conservative value, a mid range value, and an optimal value.

Each NPV was calculated the same way. The time period chosen for the LCEA was 45 years. This time period was chosen because this is a conservative estimate for the life of a green roof. Green roofs are predicted to last 30-60 years (USAF, 2003; Osmundson, 1999, 153). There are fully functional green roofs in Germany known to be 60 years old (Haupt, 2003). Asphalt BURs tend to have a variable range in life spans. This variation in life spans is likely due to the climate where the roof is located as well as the quality of the installation effort. The typical range given for a BUR is 10-20 years (Schierer, 2003; Perry, 2003a), but a study of over 25,000 roofing systems in use between 1975 and 1996 shows the average life span of an asphalt BUR is 13.6 years (Hoff, 2003). A conservative 15-year life span was used for LCEA.

IV. RESULTS AND DISCUSSION

4.1 Introduction

The results of this research process are explained and illustrated in this chapter. First, information obtained from site visits, case studies found within the literature, and independent research investigations was summarized. Secondly, assumptions necessary to complete the life cycle economic analysis of the roofing system are stated. Thirdly, the cost estimates for each roof are shown, and life cycle costs are calculated showing the best economic alternative roof system for Building 15 at AFP4. This chapter attempts to answer the main research questions posed in Chapter 1. These questions include:

1) Where have green roofs been used successfully in the past and what are the characteristics, benefits, and problems encountered with those roofs?

2) What is a viable green roof design for Building 15 at AFP4 based on successful green roof applications and the recommendations of experts in the green roof industry?

3) What is the life cycle cost of a green roof and the conventional roofing system that would be used at AFP4?

4) What are the anticipated characteristics, benefits, and maintenance requirements for a green roof at AFP4?

4.2 Case Study Summaries and Literature Information

4.2.1 Case Study Summaries

Unless otherwise noted, photographs of roofs were taken by the author.

<u>Building 15 at Air Force Plant 4</u> (Harrison, 2003; Mockler 2003)

Overview: Building 15, shown in Figure 4.1, was chosen as the facility on which to install a vegetated roof as a test case. The roof's performance will influence the decision to use green roofs on other LM and AF facilities in the future. The facility was chosen as the building for the test case because it does not house any activities vital to the production of aircraft, and it has a large roof (over 100,000 ft^2) that would magnify the beneficial or negative effects of the roof's performance. It is also much smaller than the original building chosen for the green roof installation; Building 4 with a roof surface of 1.6 million ft^2.

Size: 101,430 ft^2

Cost: \$1,072,083 or \$10.57/ft^2**.** The cost estimate was developed by Mike Perry, President of Building Logics in Virginia Beach, VA. The company specializes in vegetated roofing technologies. The actual cost estimate is shown in Appendix B, and is the main focus of this work. The estimate encompasses the entire job from mobilization to close out as well as taxes, overhead and profit.

Location: Fort Worth, Texas

Anticipated Benefits: Upon completion of the roof installation and the vegetation reaching maturity, this facility will likely realize summertime energy savings of 20-25% equating to a \$10,000 - \$12,000 savings per year (Perry, 2003a; Scholz-Barth, 2001). The roof is designed to retain between 50% and 75% of the rainfall that it receives. Normally, almost all rainfall would become storm water runoff and potentially cause the degradation of nearby bodies of water. The average monthly rainfall in Ft. Worth is 2.9 inches per month (National Weather Service, 2003). With this level of rainfall the vegetated roof will retain between 90,000 and 140,000 gallons of water each month (calculations shown in Appendix B). The vegetated roof will likely last 40 –

60 years (Perry, 2003a: Osmundson, 1999:153), saving thousands of dollars that could be spent on future replacements of asphalt BURs. The roof will likely contribute to the reduction of the urban heat island effect while improving air quality in the microclimate, and insulate inside users from extreme exterior noise levels such as the aircraft using the nearby runway. The green roof will ultimately return the rooftop to a vibrant ecosystem.

Roof Components:

Insulation: ISO insulation and HD Fiberboard.

Membrane and root barrier: Famogreen Ret.

Growing medium: Three inch blend of mineral rock, sand, and organic soil.

Vegetation: Plant plugs (sedums).

Figure 4.1 Building 15 at AFP 4 in Ft. Worth, TX. Building 15 has over 100,000 ft^2 of roof. (Rowls, 2003)

<u>Chicago City Hall</u>

Overview: The Chicago City Hall roof, shown in Figures 4.2 – 4.6, is the focal point of an initiative by the mayor and city government of Chicago to reduce the Urban Heat Island Effect (UHIE) in the city (Laberge, 2003:1). The roof has both intensive and extensive roof gardens and extensive walkways and maintenance paths. There are over 150 different plant species on

the roof including sedums, flowers, vines, shrubs, and two trees (City of Chicago, 2003a:3). The annual cost of maintaining the semi-intensive green roof is $4000 (City of Chicago, 2003a:4). Savings realized from reduced cooling and heating costs offset the maintenance costs. There are birdhouses on the rooftop to attract wildlife. Besides being a beautiful roof garden, the rooftop is a laboratory from which water runoff and pollution reductions are measured. The results of the studies being performed on the roof will influence recommendations for future roofing guidelines for the city to further combat pollution and the UHIE (Chicago, 2003a:2).

Size: Roof area is 38,000 ft^2. Vegetated area is approximately 21,700 ft^2. (11,800 ft^2 of the roof is extensive roofing, 9,800 ft^2 is semi-intensive, and 100 ft^2 is intensive. (Kiers, 2002:87))

Cost: $1.5 Million or $39/$ft^2$. The high cost was due to repairs to the roof and building structure necessary before the green roof could be installed. The vegetated roofing system only cost $500,000, or $23/$ft^2$ (City of Chicago, 2003a:4). That cost included extensive, intensive, and semi-intensive cost. The semi-intensive and intensive portions increased the average cost per square foot considerably. Another cost consideration was the height of the roof. Getting materials on the roof was a laborious endeavor.

Location: Chicago, Illinois

Benefits: Tests have shown that the green roof above City Hall is typically 25 – 80 ^{o}F cooler than the adjoining black tar roof above the county's portion of the building (Dawson, 2002). This major temperature reduction has allowed City Hall to reduce its summer energy bill by $4000 (USAF, 2002:8; Chicago,undated-a:2). The money saved in cooling costs is enough to pay for the roof's annual maintenance. The roof has become a showcase item for the city in its initiative to reduce the urban heat island effect. The roof offers multiple environmental benefits by providing wildlife habitat, producing oxygen while absorbing carbon dioxide, retaining storm

water, and slowing the chemical reactions that produce substances found in smog. The rooftop can be seen from taller buildings that surround City Hall and provides a pleasant aesthetic improvement to the view below.

Roof Components: (Laberge, 2003)

Water proofing membrane: Single ply thermal polyolefin (TPO) from Sarnafil.

Root barrier: Installed by Bennett and Brousseau.

Drainage layer: Drainage mat and roasted Arkansas clay installed by Roofscapes.

Filter fabric: Installed by Roofscapes.

Growing Medium: Lightweight custom growing mixture by Roofscapes, Inc.

Vegetation: Over 150 species of plants.

Biodegradable wind blanket (degrades within 2 years)

Figure 4.2 Chicago City Hall Green Roof. Note the black roof on the county's portion of the building in the back right.

Figure 4.3 Chicago City Hall Roof. Notice the beehives and pathways on the roof. Bees help facilitate the pollination of the plants on the roof.

Figure 4.4 City Hall Roof. Note the variety of plant species on the roof as well as the extensive versus the deeper semi-intensive sections of the roof.

Figure 4.5 City Hall Roof. Chicago City Hall is approximately 8 stories above the street level. Materials were placed on the roof by crane and freight elevator.

Figure 4.6 City Hall Roof. The roof supports a variety of plant species which exhibit multiple colors.

<u>Ford Motor Company's Truck Manufacturing Facility</u> (Russell, 2003; Monterusso, 2003)

Overview: In Ford Motor Company's effort to be environmentally proactive, leadership made the decision to install a vegetated roof on the new truck manufacturing facility in Dearborn, Michigan. The roof, shown in Figures 4.7 and 4.8, is just one of many environmental restoration efforts that Ford has undertaken to restore the environmental health of the surrounding 11,000 acre Ford complex. Completed in November 2002, the Ford roof is the largest vegetated roof in the world (Russell, 2003). The vegetation on the roof consists of 13 species of sedums. The

sedums have different growing seasons that overlap, but most species go dormant in the winter and change from lush green to reddish brown in color. This characteristic of the plants gives the roof an aesthetically pleasing appearance year round that visitors can enjoy from an elevated observation room.

Size: 454,000 ft^2.

Cost: \$4,994,000 or \$11/ft^2

Location: Dearborn, Michigan.

Benefits: The roof is only a year old and production activities have not begun in the facility, so the expected benefits have not been validated at this time. In an effort to install the roof before winter 2002, the plants (installed as vegetated mats that were grown locally) provided only 70% coverage. After a summer growing season, the plants provide 100% coverage. After the plants reach maturity, the vegetated roof is expected to provide all the environmental benefits for which green roofs are known.

The roof is expected to provide significant rainfall retention to reduce storm water runoff. The system is designed to absorb a portion of the rain it receives and will weigh 11 lbs/ft^2 when saturated versus its dry weight of approximately 6 lb/ft^2 (Monterusso, 2003). Each square foot of the roof is capable of retaining five pounds of water, or 0.6 gallons of water, during a rainfall event – a significant volume of water that is not carrying pollutants to lakes and streams. Over the course of a year, the green roof is anticipated to reduce storm water runoff by 4.5 million gallons – enough to fill almost six Olympic sized swimming pools (Ford, 2003). The roof structure was designed with the water retention capability in mind and has a structural capacity of 25 lb/ft^2.

In addition to storm water retention, the roof provides a cooling effect for the facility. The cooling effect of the roof is anticipated to reduce summertime air conditioning requirements. This cooling effect will translate to a minimum of 5% - 10% reduction in energy cost which is a significant savings when considering the cost to provide conditioned air for 1.2 million ft^2 of floor space. Another benefit was seen this past spring, the roof's first, when barn swallows were seen nesting on the roof – a sign that the roof is attracting wildlife to the area as expected.

The roof will provide these types of benefits for 40 – 60 years (Russell, 2003; Osmundson, 1999:153). Studies on similar systems in Germany are producing data that indicate the roofing system will last that long (Haupt, 2003; Osmundson, 1999). As of now, the total benefits provided by the roof are unknown, but in a short time, Ford will reap the rewards of installing a vegetated roof.

Roof Components: (Monterusso, 2003; Russell, 2003)

Insulation: 1.5 inch Isocyanurate insulation fastened to metal roof deck and ¾ inch Perlite adhered with hot asphalt to Isocyanurate insulation. Both insulations were made by Johns Manville.

Waterproofing membrane – Paradiene 20 covered in type IV asphalt and Teranap (a modified bituminous, torch applied membrane). Both pieces of the membrane were made by Siplast.

Root barrier: High Density Poly Ethylene sheets overlapped by 12 inches.

Drainage layer and filter fabric: Enkadrain by COLBOND Geosynthetics. This drainage system is a plastic "mesh" with a layer of filter fabric attached to one side. The product is lightweight and flexible.

Water retention: Two layers of lightweight fleece material – capable of holding water for plants during dry periods. A 1200 gram layer of fleece was laid loosely at the time of installation. An

800 gram layer of fleece was attached to vegetation "carrier" – a fabric to help hold the plants together during installation. The water-retention fleece is made of recycled materials.

Growing medium: The mats were grown nearby on the surface of a capped landfill. Growing medium was place on the ground surface and seeded. When the mats were harvested and placed on the roof, they only had 0.5 inches of growing medium held in place by the plant's root system and the "vegetation carrier". The growing medium consists of expanded shale, sand, peat, compost, and dolomite. Portions of the mixture were developed by Carolina STALITE Company and other components were obtained locally.

Vegetation: 13 species of sedum

Figure 4.7 Ford Roof. The Ford River Rouge truck manufacturing plant roof is currently the largest green roof in the world. A light monitor (seen in background) allows natural light into the plant.

Figure 4.8 Ford Roof. Workers from the installation contractor maintained the roof for one year after installation (Russell, 2003).

<u>Oldenburg Bus Station</u> (Behrens, 2003)

Overview: The city of Oldenburg realized the potential benefits of vegetated roofing when looking for the optimum roofing solution for its bus station eight years ago (Behrens, 2003). The vegetated roof system (shown in Figures 4.9 – 4.12) was selected for its longevity and maintenance free qualities. The city was able to reduce long term operational cost by choosing a vegetated roofing system. The users have been pleased with the roof's performance.

Size: 5500 m^2 or 59,216 ft^2

Cost: \$275,000 or \$4.64/ft^2

Location: Oldenburg, Germany

Benefits: The roofing system provides several environmental benefits and saves the user money in multiple ways. The user pays only 50% of its original "rain tax" imposed by the German government (Behrens, 2003:2) because water from the bus station complex entering the storm sewer is greatly reduced. Studies indicate that roof can retain approximately 60 liters/m^2 or 1.47 gallons/ft^2 (Behrens, 2003:2). Water not absorbed by the roofing system is collected in underground storage containers and used to wash the buses. The water is clean enough to use on the buses as it has been filtered by the green roof and a filter in the drainage system leading to the cistern. In addition to cleaning the water used to wash the buses, the roof is maintenance free. The user has done no work on the roof since it was installed eight years ago, and has had no problems with its performance. However, the green roof company that installed this roof recommends a minimum level of maintenance – typically an annual application of fertilizer and weeding.

Roof Components: (Behrens, 2003)

Root barrier: 1.5 mm thick PVC-Film developed by Sarnafil.

Root protection: The Sarnafil membrane has inherent root protection.

Insulation: Eight cm thick hydroscopic mineral wool located under the waterproofing membrane.

Drainage: Xero Drain, developed by Xeroflor.

Growing medium: Four cm of mineral wool. This is a very lightweight material with excellent water retention capabilities. It is rolled out on top of the drainage layer. The vegetated mats are placed directly on the mineral wool. Due to the absence of a typical growing medium, the vegetation mats are supposed to be fertilized annually in the spring. However, the bus station management has not applied the fertilizer in the last four years. The plants do not appear to be suffering from the absence of the annual fertilizer application.

Vegetation: Vegetated mats consisting of sedums and mosses were placed end to end on the roof. Plant roots grew down into the mineral wool to retrieve moisture. This roof is unique in that the customer requested that the mats be grown with coconut fibers in them as a mulch-like, soil substance. Within the first couple of years the system was in place, the coconut fibers shrunk, which caused the mats to shrink, and left gaps between the vegetation mats. Within a short time, mosses filled in the open spaces between the mats. Another type of vegetation has appeared in the low spots near the roof drains. In these areas the roof components have a higher moisture content, and wild onions have grown “voluntarily”. Many facility owners would remove these voluntary plants, but the facility manager for the bus station has chosen to do no maintenance on the roof and let its existence be completely natural.

Figure 4.9 Oldenburg Bus Station. Atypical roof. Vegetated mats made with coconut fibers that later shrunk leaving gaps between the mats. Gaps filled in with mosses.

Figure 4.10 Oldenburg Bus Station. Wild onions have grown in the low spots near the drains

Figure 4.11Green Roof Drain. Gravel around drain facilitates drainage. Sedums are beginning to creep into the gravel area.

Figure 4.12 Green Roof Mats. No growing medium was used on this roof except the substrate in which the mats were grown before installation.

<u>Oldenburg Air Base Bunker 1</u> (Behrens, 2003)

Overview: Fourteen years ago NATO initiated a study to determine the camouflaging benefits of vegetated roofing for military purposes. The study was to determine if vegetated roofing would cause the facility to blend with the surrounding landscape as seen from overhead. Approximately 450,000 square meters (4,842,000 square feet) of different types of vegetated

mats were installed on military bunkers and other facilities to see which types of mats were best suited for camouflaging a facility.

Bunker 1, shown in Figures 4.13 – 4.16, was one of three facilities chosen in July 2003 for study. There are variations in each of the three roofs. Bunker 1 is an above ground, concrete bunker with an arch-like structure. Having an arch-like shape, the entire exterior of the building, minus the ends, was covered with vegetation.

Five centimeters of soil was placed on the top of the bunker where there was only a slight slope at the top of the arch, and no soil was placed on the sides of the bunker where the slope was excessive. The soil would have eroded as the sides became almost vertical. The vegetated mats were grown elsewhere with the plants growing through a lightweight, flexible, plastic sling/coil. The purpose of the coil was to hold the mats together when they were placed on the sides of the bunkers where the pitch was almost vertical. After the plants were mature, the mats were harvested in long strips that, when placed on the bunker, reached from one side to the other. They were approximately four feet wide. Other than the plastic sling/coil, the mats were placed on the bunker with no additional support on the sides to prevent portions of the mat from tearing and sliding off of the building. After installation of the vegetation, no additional maintenance or care was performed on the vegetation. The study revealed that installing the vegetation in this manner was not an adequate way to camouflage a facility. The plants on the southern/sunny side of the bunker were surviving, but were reddish in color. The plants turned red because the mats did not have enough soil to retain water. The extremely dry conditions bring about the reddish color. The plants on the top of the arch were more of a green color because the 5 cm of soil under the mats has not eroded and retains enough moisture to nourish the plants. The studies for the camouflaging potential of green roofs have concluded and the roofs are not maintained to

ensure their proper, long term performance. Even after more than a decade of neglect, the vegetation is still surviving.

Size: 750 m^2 or 8070 ft^2.

Cost: Unavailable.

Location: Oldenburg Air Base, Germany.

Benefits: The green roofs do have the potential to offer some concealment to military facilities. Portions of the roof blend with the surrounding vegetation in the area. However, the reddish colored portions of the vegetation present a stark contrast to the green vegetation in the vicinity of the facility. Preventing the reddish color from appearing would be a simple matter. Providing adequate soil depth or a water retaining component to the roof would likely keep the plants green.

Roof Components:

Waterproofing membrane: None used. Concrete bunker did not need a sealant.

Root barrier: N/A.

Insulation: N/A.

Drainage Layer: Xero Drain.

Substrate: 1-5 cm of Xero Terr. The mixture meets the German FLL standards and consists of 70% lava rock of varying size, 5% dolomite, 25% dry tree bark. After the previous components are blended, 2% clay is added.

Vegetation: Xeroflor mats.

Figure 4.13 Bunker 1. Signs of neglect are evident.

Figure 4.14 Bunker 1. The top of the bunker is flat enough that soil can remain in place.

Figure 4.15 Bunker 1. The steep sides of the bunkers are not as conducive for plant growth without additional mechanisms to support a growing medium.

Figure 4.16 Bunker 1. The plastic sling/coil that holds the mats in place can be seen through the sparse vegetation.

Oldenburg Air Base Bunker 2 (Behrens, 2003)

Overview: Bunker 2, shown in Figures 4.17 and 4.18, was identical to Bunker 1, an above ground, arch-like, concrete bunker. However, before the vegetated roof was installed, concrete walls were added to the sides of the bunker to allow greater depths of soil and to significantly reduce the pitch of the sides of the roof. Because soil depths are approximately 1 meter in some locations, several large trees are growing on the bunker, adding to the camouflaging qualities of the roof.

Size: 750 m^2 or 8070 ft^2.

Cost: Unavailable.

Location: Oldenburg Air Base, Germany.

Benefits: The roof provided exceptional camouflage from above. The deeper soil depths support a greater variety of plant species and allow the plants to remain green like the surrounding vegetation.

Roof Components:

Waterproofing membrane: A PVC membrane (trade name TROCAL by German company Henkel/Dusseldorf) was applied to the exterior of the facility as a waterproofing/root resistant barrier.

Root barrier: TROCAL.

Insulation: N/A.

Drainage Layer: Xero Drain.

Substrate: 20 cm to 1 meter of topsoil.

Vegetation: Currently, native grasses and volunteer plants dominate the roof.

Figure 4.17 Bunker 2. With soil depths ranging from 20 cm to 1meter, the intensive roof on bunker 2 is able to sustain large trees as well as other vegetation.

Figure 4.18 Bunker 2. Bunker 2 provides excellent camouflaging effects from overhead by sustaining grasses and other woody stemmed plants.

<u>Oldenburg Air Base Bunker 3</u> (Behrens, 2003)

Overview: Building 3, shown in Figures 4.19 – 4.22, was a warehouse facility. The building had vertical walls and a flat roof and was used as a warehouse. The roof was bi-level. Most of the roof area was an extensive vegetated roof, but some portions were intensive. There were two small areas where no vegetation was planted; exposed gravel was on the surface. The soil depth varied in different locations on the roof and ranged from no soil in some locations to 25 cm in the deepest section. The gravel drainage system and the deeper soil depths on portions of the roof create a considerable load on the roof structure. The heavier sections weigh 340 – 550 kg/m^2 (70-110 lbs/ft^2). On the extensive portions of the roof, vegetation mats were installed. In the smaller, intensive sections of the roof, shrubs and grasses were planted. The camouflaging study was discontinued after the first several years the roof was in place. After over a decade of neglect, some portions of the roof were thriving more than others. Sedums were creeping into the areas that had only exposed gravel. The areas of the roof with only vegetated mats and no soil could be seen distinctly because they were reddish in color and were in contrast with the rest of the “green” roof – not good for camouflage. To maintain adequate camouflaging effects, soil is required to sustain all plants or minor maintenance is necessary. Even with no maintenance, the roof is functioning properly from a roofing perspective.

Size: 750 m^2 or 8070 ft^2.

Cost: Unknown.

Location: Oldenburg Air Base, Germany.

Benefits: The roof shows the durability and the effectiveness of vegetated roofing. The roof is 14 years old. At this age, many asphalt BURs would need to be replaced or would be nearing the end of their effective performance. This green roof is still performing effectively as a green roof,

and has received no maintenance. In addition to the longevity of the roof, it demonstrates the potential to camouflage a facility from overhead by installing a green roof. However, the roof also shows that minor upkeep efforts and adequate amounts of soil are necessary to ensure the desired camouflaging effects are realized.

Roof Components:

Waterproofing membrane: A PVC membrane (trade name TROCAL by German company Henkel/Dusseldorf) was applied to the exterior of the facility as a waterproofing/root resistant barrier.

Root barrier: TROCAL.

Insulation: Unknown – installed under roof deck.

Drainage Layer: Gravel.

Substrate: Xero Terr by Xeroflor. The mixture meets the German FLL standards and consists of 70% lava rock of varying sizes, 5% dolomite, 25% dry tree bark. After the previous components are blended, 2% clay is added.

Vegetation: Xeroflor vegetation mats, shrubs, and grasses.

Figure 4.19 Building 3. The Building 3 roof has varying conditions such as exposed gravel, no soil, and multiple soil depths.

Figure 4.20 Building 3. Only sedums remain on the portions of the roof with only gravel and no soil.

Figure 4.21 Building 3. The roof looks like an open field and this section of the roof provides excellent camouflage.

Figure 4.22 Building 3. Only sedums exist on the raised portions of the roof with no soil.

<u>Geestacht Apartments</u> (Haupt, 2003)

Overview: This two year old apartment building, shown in Figure 4.23, allows many residents to enjoy the benefits of a vegetated roof. At the time of the visual inspection, Northern Germany was experiencing a severe drought. The dry conditions had begun to stress the plants on the ground, and the extreme conditions on the roof were more harsh. However, the hardy sedums on the roof had not died or wilted, but with the heat and dry conditions, the plants had become a reddish color. Green roof experts Bert Haupt and Mike Perry, presidents of Famos and Building Logics, respectively, explained that this color change is a common characteristic of sedums in dry conditions. Haupt and Perry said the plants would rapidly return to their more common greenish color after a rain. The refuse collection shelter for the apartment complex, shown in Figure 4.24, also has a vegetated roof. The roof filters rainwater and prevents runoff in addition to adding greenery to the landscape. The roof was most likely "greened" because it helps meet regulations for replacing green space that has been developed.

Size: Approximately 400 m^2 or 4304 ft^2.

Cost: Unknown.

Location: Northern Germany.

Benefits: Specific benefits have not been measured. However, the fact that there are no air conditioners in the apartments indicates that at least some cooling benefits are being realized.

Roof Components:

Waterproofing membrane: Famogreen Ret.

Root barrier: Famogreen Ret.

Insulation: Unknown.

Drainage Layer: Famogreen Ret.

Substrate: Unknown.

Vegetation: Xeroflor vegetation mats.

Figure 4.23 Apartment Building. The vegetation on the 2 year old apartment building was installed as vegetated mats.

Figure 4.24 Refuse Shelter. The water retention benefits and aesthetics of vegetated roofing make it worthwhile for Germans to install vegetation on small refuse sheds.

<u>Poeseldorf Apartments</u> (Haupt, 2003)

Overview: This collection of roof spaces on several levels is over apartments that are built above small stores and shops. A view from above is shown in Figure 4.25. The roofs were installed 31 years ago before roofing technology was developed specifically for green roofs, so some of the typical components are missing – such as a drainage system. The green roof sections are

intensive and are supporting vibrant roof gardens. The intensive roofs receive some maintenance, but the company that installed the roof is not aware of any problems or major repairs occurring on the roof. A visual inspection in July 2003 revealed that the membrane is in excellent condition.

Size: 600 m^2 or 6456 ft^2.

Cost: Unavailable.

Location: Poeseldorf, Germany – near Hamburg, Germany.

Benefits: Longevity – the roof is 31 years old and is in excellent condition with little or no maintenance to the waterproofing membrane. The intensive roof gardens enhance the urban landscape by providing greenery for apartment residents and shoppers in an area full of multi-story buildings.

Roof Components:

Waterproofing membrane: Actactic Polypropylene (APP) was torched to the roof deck.

Root barrier: APP with chemicals.

Insulation: Polystyrene.

Drainage Layer: None.

Substrate: 24-48 cm or 9.5-19 inches of topsoil.

Vegetation: A mix of bushes, flowers, shrubs, etc. suitable to an intensive green roof.

Figure 4.25 Poeseldorf Apartments. Intensive green roofs provide cooling benefits for shops below and aesthetics for the apartments above.

<u>Elbe Center Department Store</u> (Haupt, 2003)

Overview: The Elbe Center roof is a large extensive green roof installed over a department store in downtown Hamburg, Germany. This green roof is shown in Figure 4.26. The vegetation surrounds panels of skylights that run the length of the building. Skylight panels can be opened to utilize natural ventilation for the building. The facility does an excellent job of utilizing the resources the natural environment offers. The skylights allow sunlight to enter the building while the natural air flow provides ventilation. The green roof provides a cooling effect that reduces the need for air conditioning.

Size: 28,000 m^2 or 301,280 ft^2.

Cost: Unknown.

Location: Hamburg, Germany.

Benefits: The roof is approximately nine years old and requires little or no maintenance (Haupt, 2003). The store below realizes significant cooling benefits and is able to meet the greening requirements mandated by the city of Hamburg (75% of any green space that is developed has to be replaced by installing a green roof or restoring a brownfield site (USAF, 2002:6)). "Rain

taxes" are significantly reduced because of the water retention capabilities of the roof. The roof also provides a pleasant view for the apartment residents across the street.

Roof Components:

Waterproofing membrane: Unknown.

Root barrier: Polybit membrane with Preventol chemicals.

Insulation: Polystyrene.

Drainage Layer: Unknown.

Substrate: 6-8 cm or 2.4-3.1 inches of mineral rocks and sand along with some organic soil

Vegetation: Sedums that were installed by hydro seeding.

Figure 4.26 Elbe Center Department Store. The cooling benefits of the roof and the ventilation from the open skylights eliminates the need for air conditioning.

<u>WIRO GmbH (Roofing Company)</u> (Haupt, 2003)

Overview: This roof was located approximately 6-8 stories high atop the WIRO GmbH offices in Rostock, Germany. The roof is shown in Figures 4.27 and 4.28. The plants were reddish in color due to the drought that Northern Germany was experiencing during the summer of 2003.

Even during the drought conditions, the sedum was growing into a gravel drainage area that had no other growing substrate.

Size: 300 m^2 or 3228 ft^2.

Cost: Unknown.

Location: Rostock, Germany.

Benefits: A concrete walkway to the center of the roof allows facility occupants to enjoy the beauty and fresh air the roof has to offer. The aesthetics of the roof coupled with the surrounding area are picturesque. The facility overlooks a large river lined with sail boats, large trees, and other beautiful, historic buildings. The roof has a fence around the walkway to ensure the safety of those that visit the roof. The roof does not require any extensive maintenance while providing the water retention and cooling benefits common to green roofs.

Roof Components:

Waterproofing membrane: Famogreen Ret.

Root barrier: PREVENTOL chemical protection. When the membrane was manufactured, the chemical was mixed with the other components used to make the membrane.

Insulation: Unknown. This roof was replaced 2.5 years ago and no new insulation was added. Insulation is under the roof deck.

Drainage Layer: Famogreen Ret has inherent drainage.

Substrate: Xeroflor mixture.

Vegetation: Xeroflor mats.

Figure 4.27 WIRO GmbH Roof. Facility occupants take work breaks on this extensive green roof.

Figure 4.28 WIRO GmbH Roof. Slender sedum roots can be seen on the bottom of the vegetated mats and broken off on the Famogreen Ret membrane underneath the mats. Roots grow through the white fabric to reach the water retaining gel crystals below.

Refuse sheds and carports

Green roofs are installed in numerous other places throughout Germany including refuse sheds and carports. Examples are shown in Figure 4.29 and 4.30. In Germany, many local governments enforce a "rain tax" based on the amount of impervious surface on a person's property. Impervious surfaces create storm water runoff and can stress storm sewer systems and water treatment facilities. Storm water also degrades streams and lakes by depositing pollution into them. In an effort to reduce storm water runoff, the governments offer incentives to those who create pervious surfaces; i.e. porous pavements and green roofs. The roofs reduce runoff while simultaneously beautifying the city.

Figure 4.29 Green Roof Shed. Green roofs are installed on refuse sheds in Rostock, Germany to retain rainwater and reduce the "rain tax" Germans pay for storm water runoff. This roof is located a short distance from the WIRO roof.

Figure 4.30 Green Roof Carport. Green roof over a carport – reducing storm water runoff.

A brief summary of the German roofs is shown in Table 4.1. Roof areas, components, and ages are highly varied indicating the differences in roofs.

Table 4.1 German green roof matrix.

Building	Age of Roof (yrs)	Roof Area	Type	Membrane Type	Depth of Substrate	Method of Plant Inst.
Bus Station	8	5500 sm	Extensive	Sarnafil root barrier	Mineral wool	Xeroflor mats
Oldenburg Air Base						
- Bunker 1_	14	750 sm	Extensive	Trocal	5cm-top, 1cm-sides	Xeroflor mats
- Bunker 2	14	750 sm	Both	Trocal	varying 20cm - 1m	Xeroflor mats
- Building 3	14	750 sm	Intensive	Trocal	6,8,10, 25 cm	Xeroflor mats
Geesthacht apts	2	- - - - - - - - -	Extensive	Famogreen Ret	none	Xeroflor mats
Poeseldorf	31	600 sm	Intensive	APP	24-48 cm	shrubs, flowers planted by hand
Elbe	9	28000 sm	Extensive	- - - - - - - - - - - - -	6-8 cm	hydroseeded
WIRO office building	2.5	300 sm	Extensive	Famogreen Ret	1.5 cm	Xeroflor mats

4.2.2 Thermal Performance and Energy Efficiency

One of the most important aspects of the green roof is its ability to protect the waterproofing membrane. One way green roofs protect the membrane is by reducing the expansion and contraction a roof membrane undergoes each day. This "stretching and shrinking" is due to the extreme temperature fluctuations experienced on a roof top. Reducing this phenomenon is one of the reasons for the extended roof life green roofs provide. A second positive aspect of the performance of green roofs is the energy

savings they provide. By reducing the heat flow into and out of a building, heating and cooling costs can be reduced.

Liu of the National Research Council (NRC) of Canada led research that determined the thermal performance and the energy efficiency of a vegetated roof compared to a conventional asphalt BUR (Liu and Baskaran, 2003:1). The study was able to demonstrate the extent green roofs protect the waterproofing membrane from temperature fluctuations and how much heat flow through the roof is reduced. The experiment compared a 2-ply modified bitumen roof and a vegetated roof. The test took place in Ottawa, Canada on a facility within the NRC's campus from November 22, 2000 to September 30, 2002. A 778 ft^2 roof area was divided equally by a small parapet wall to separate the conventional roof and the extensive vegetated roof. The roof was representative of a low slope industrial roof.

The conventional roof was similar to asphalt BURs constructed throughout the United States and Canada. Above the roof deck, a vapor retarder, thermal insulation, and fiberboard were applied before a 2-ply modified bitumen membrane was installed. The cap sheet of the roof was covered with light grey granules. Grey granules were chosen rather than highly reflective white or heat absorbing, black granules which might produce extreme temperature values during the experiment.

The vegetated roof was constructed in the same manner as the reference (bitumen) roof with additional components on top. Both roofs are shown in Figure 4.31. A root repellent was added to the waterproofing membrane on the green roof as it was installed. Then a drainage layer, filter fabric, and six inches of light-weight growing medium were put in place. Plants that would resemble a wildflower meadow were planted in the

substrate for the first year of observation and typical lawn grass (Kentucky blue grass) was added for the second year of observation.

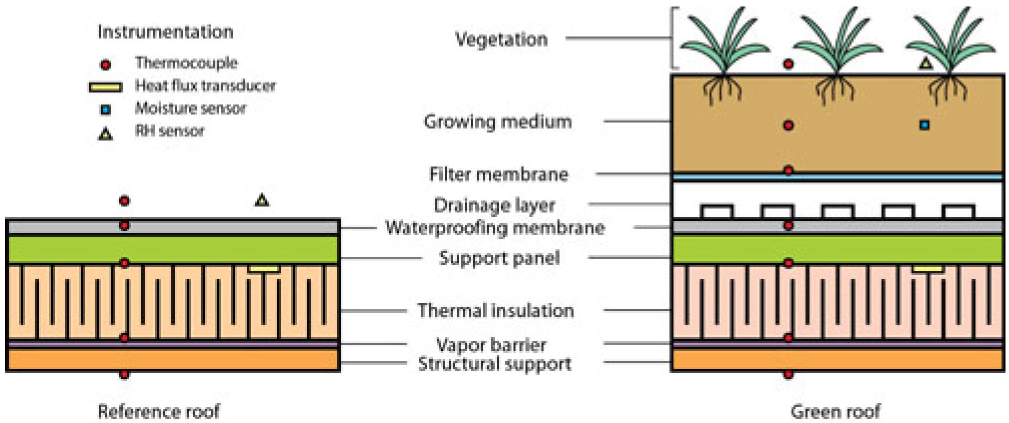


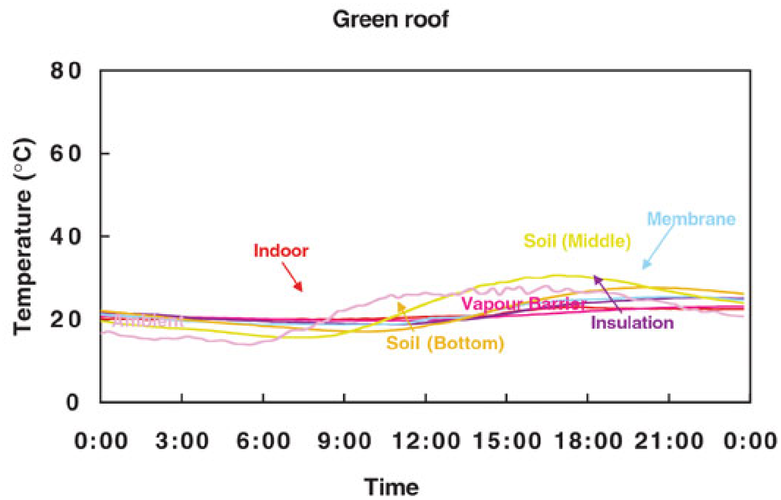
Figure 4.31 Roof Components. Major components and instrumentation of the green roof system and reference roof system are shown. (Liu and Baskaran, 2003).

Multiple tools and sensors were installed on the roof to measure various aspects of the roofs' performances. Sensors to measure temperatures were placed at multiple levels in each roof. On the reference roof, temperature readings were taken on the membrane, insulation, and vapor barrier surfaces as well as inside the building and the ambient air above the roof. On the green roof, temperature readings were taken in the middle of the soil, the bottom of the soil, on the insulation and vapor barrier, in the air above the green roof, and in the building directly below the green roof. The data collected on a hot, sunny day yielded the graphs seen in Figure 4.32 and the trends from the entire observation period are seen in Figure 4.33. The plot of the temperatures of the roof layers over the course of the day and the tabular data show that the green roof has a significant dampening effect on the temperature fluctuations of the components under the vegetation. Over the course of the study, the median temperature fluctuations for the reference roof were 81 ^{o}F compared to 11 ^{o}F for the green roof (Liu and Baskaran,

2003:3). Temperature data from 660 days of observation on the roof are captured in Table 4.2.

Table 4.2 Roof Temperatures. Statistics on the daily maximum temperature of the roof membranes on Field Research Facility during the observation period (660 days in total). (Liu and Baskaran, 2003)

Temperature Greater Than:	Reference Roof		Green Roof		Ambient	
	No. of Days	% of Days	No. of Days	% of Days	No. of Days	% of Days
30°C (86°F)	342	52	18	3	63	10
40°C (104°F)	291	44	0	0	0	0
50°C (122°F)	219	33	0	0	0	0
60°C (140°F)	89	13	0	0	0	0
70°C (158°F)	2	0.3	0	0	0	0



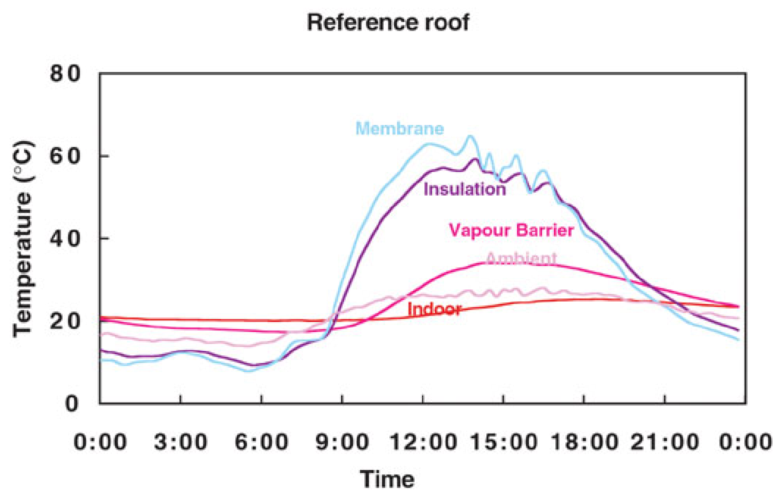


Figure 4.32 Temperature Profiles. A temperature profile within the roof systems on a hot, sunny summer day indicates the green roof system reduced its temperature fluctuations. (Liu and Baskaran, 2003)

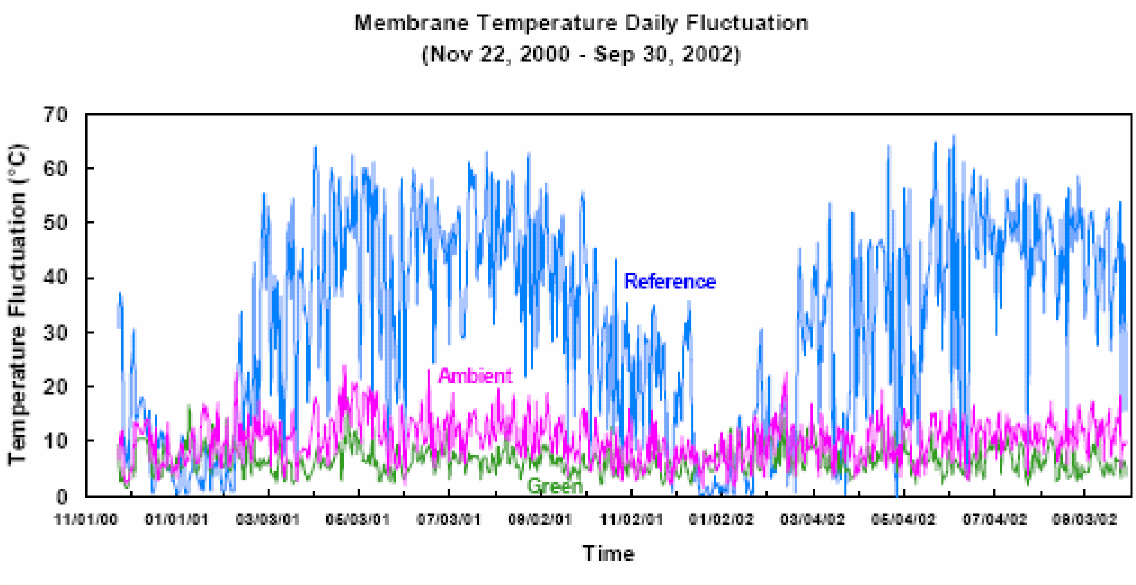


Figure 4.33 Temperature Measurements. Temperature measurements showed that the Green Roof significantly reduced the daily temperature fluctuation experienced by the roofing membrane. (Liu and Baskaran, 2003)

Liu and Baskaran (2003) also found improved energy efficiency and reduced heat flow through a vegetated roof. A green roof reduces heat gain through the roof by shading, evaporation and transpiration of the plants, and the insulating effect of the mass of all the components above the membrane. Heat gain through the roof during the warmer seasons creates a need for air conditioning while heat loss in the winter increases heating costs. Based solely on the heat flow through the roofs from April to September, the daily energy demand for air conditioning was 20,500 – 25,500 BTU/day (6.0-7.5 kWh/day) for the reference roof compared to 5,100 BTU/day (1.5 kWh/day) for the green roof – a 75% energy reduction. Liu and Baskaran's measurements are shown in Figure 4.34.

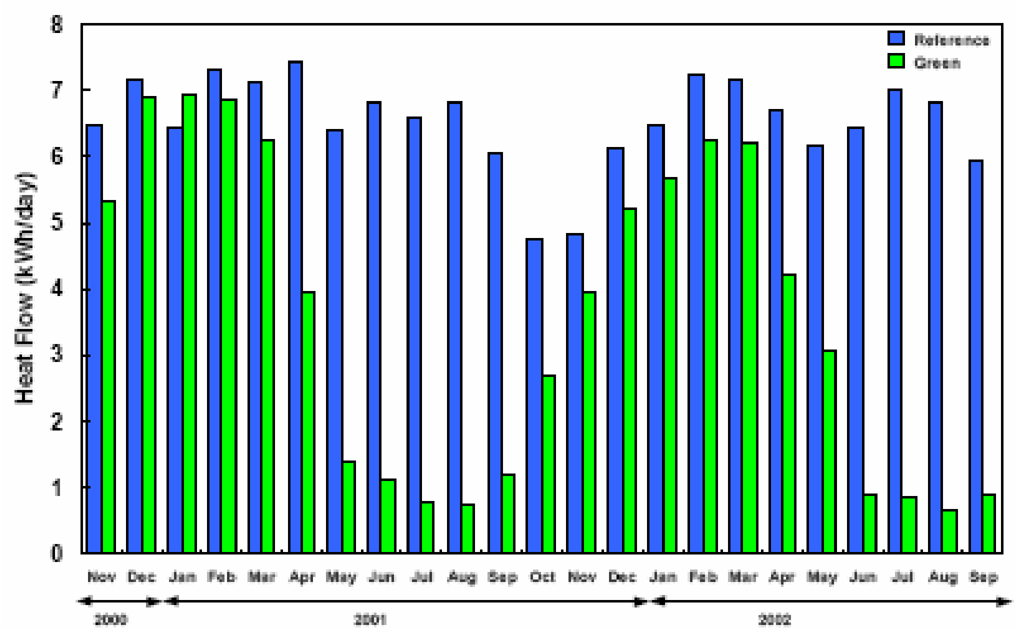


Figure 4.34 Heat Flow Measurements. Heat-flow measurements show the average daily energy demand caused by the heat flow through the green roof system was less than that of the reference roof system in spring and summer. (Liu and Baskaran, 2003)

Green roofs provide a much smaller, but measurable, insulating effect in the fall and winter months until the roof components freeze. Once the roof freezes, the insulating effect becomes negligible. However, in Ottawa and other cold areas, once snow coverage is significant, the heat flow through the roofs is lessened and is the same for both roof types (Liu and Baskaran, 2003:4). The snow acts as an insulator and stabilizes the heat flow though both roofs.

When comparing the two test roofs, the green roof reduced the roof's heat gain by 95% and reduced the heat loss by 26% as shown in Table 4.3. The green roof reduced the overall heat flow by 47% - indicating a large potential for energy savings. Noting that green roofs are significantly more effective at reducing heat gain than reducing heat loss, the savings would likely be more significant in a warmer climate.

Table 4.3 Heat Flow. Normalized (per unit area) heat flow through the roof surfaces of the field research facility during the observation period (November 22, 2002 – September 30, 2002). Figure courtesy of the NRC of Canada.

	Reference Roof	Green Roof	Reduction
Heat Gain	19.3 kWh/m^2 (5900 BTU/ft^2)	0.9 kWh/m^2 (270 BTU/ft^2)	95%
Heat Loss	44.1 kWh/m^2 (13500 BTU/ft^2)	32.8 kWh/m^2 (10100 BTU/ft^2)	26%
Total Heat Flow	63.4 kWh/m^2 (19400 BTU/ft^2)	33.7kWh/m^2 (271 BTU/ft^2)	47%

4.2.3 Storm Water Management

Storm water management is one of the major beneficial qualities of vegetated roofing. Green roofs improve storm water management in multiple ways. Two of the most significant improvements involve runoff volumes and runoff rates. When compared to conventional roofing systems, vegetated roofs significantly reduce the amount of storm water entering storm sewer systems, and they slow the rate at which the smaller volumes of water enter drainage systems (Rowe et al., 2003:1). The average green roof will retain 75% or more of a one inch rainfall (Scholz-Barth, 2001:4). Green roofs that are installed properly will release the excess water slowly over several hours as opposed to conventional roofs where the runoff enters drainage systems immediately (Rowe et al., 2003:1).

Figures 4.35 and 4.36 show the reduced volume and the time delay of runoff entering a drainage system for a summer and winter storm event, respectively. The summer storm event (Figure 4.35) is a relatively intense rainfall over a short period of time depositing 88.3 ft^3 of water. The roof retained 96% of the "run-on" from this rainfall event, releasing only 3.9 ft^3 of water (Hutchinson et al., 2003:12). The plot of the

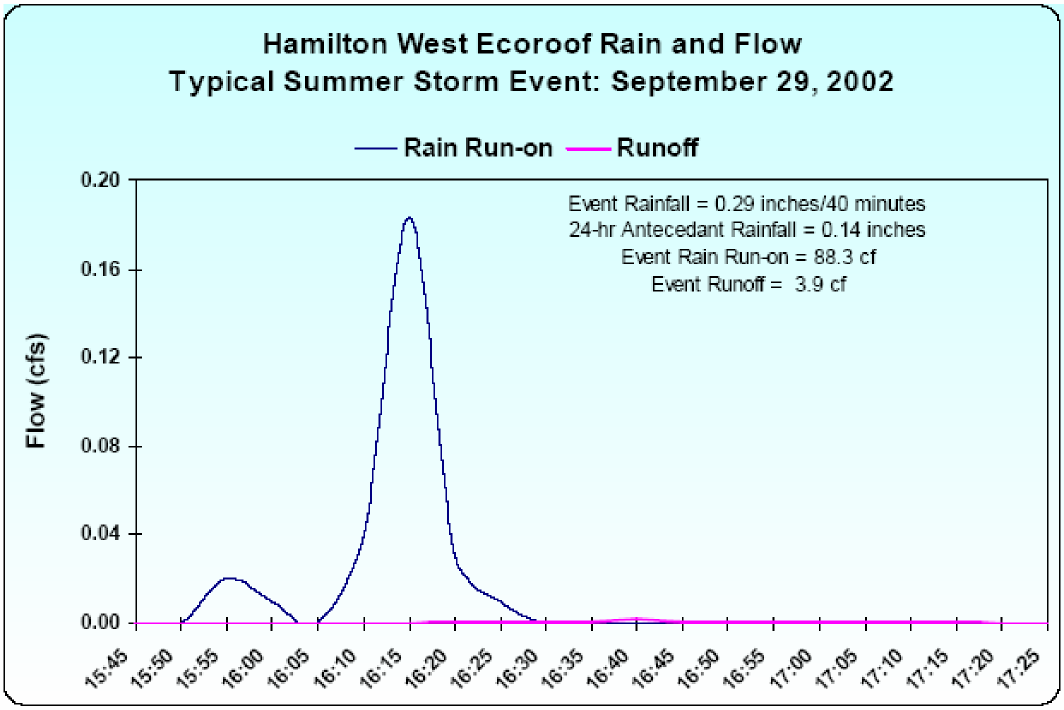


Figure 4.35 High Intensity, Short Duration Summer Storm. (Hutchinson et al., 2003)

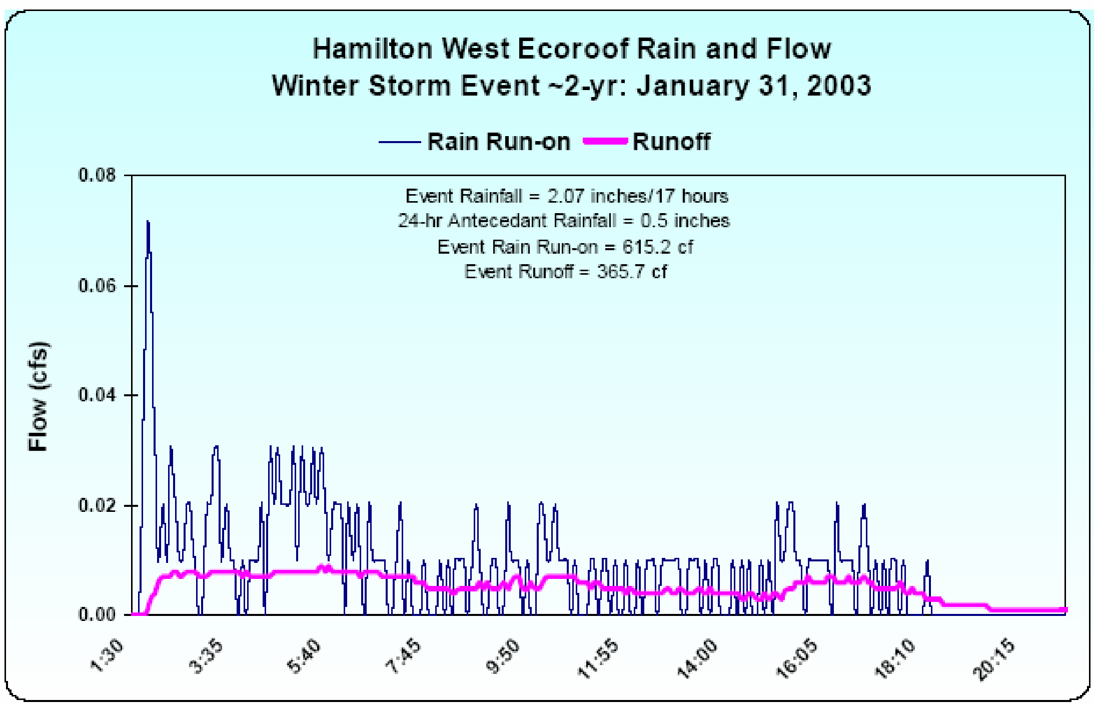


Figure 4.36 Winter Storm Event. Green roof contained a large portion of the water hitting the roof. (Hutchinson et al., 2003)

winter storm event (Figure 4.36) depicts a 2.07 inch rainfall over a 17 hour period with 0.5 inches of rain in the preceding 24 hours. With such a large rainfall, most green roofs will become saturated and the runoff reduction does not appear to be as significant, but this roof was able to retain 41% of the “run-on” volume. However, such large rainfalls are atypical in the Ft. Worth area (National Weather Service, 2003). Rainfall is shown tabularly in Table 4.4 and graphically in Figure 4.37. With smaller rainfalls (less than 1 inch in a 24 hr period), a vegetated roof would retain a much higher percentage of the overall volume of water.

Table 4.4 Rainfall data for the Dallas/Ft. Worth area (National Weather Service, 2003).

Month	**Rainfall (inches)**	**Precipitation (days)**	**Avg Rainfall/event (inches)**	**Number of days > .99 inches**
Jan	1.9	6.7	0.28	0.3
Feb	2.37	6.3	0.38	0.5
Mar	3.06	7.3	0.42	0.7
Apr	3.2	7.6	0.42	1.2
May	5.15	8.7	0.59	1.4
Jun	3.23	6.4	0.50	0.9
Jul	2.12	4.7	0.45	0.7
Aug	2.03	4.6	0.44	0.8
Sep	2.42	7.1	0.34	1.1
Oct	4.11	6.2	0.66	1.4
Nov	2.57	6	0.43	0.6
Dec	2.57	6.5	0.40	0.4
Total =	34.73	78.1	0.44	10

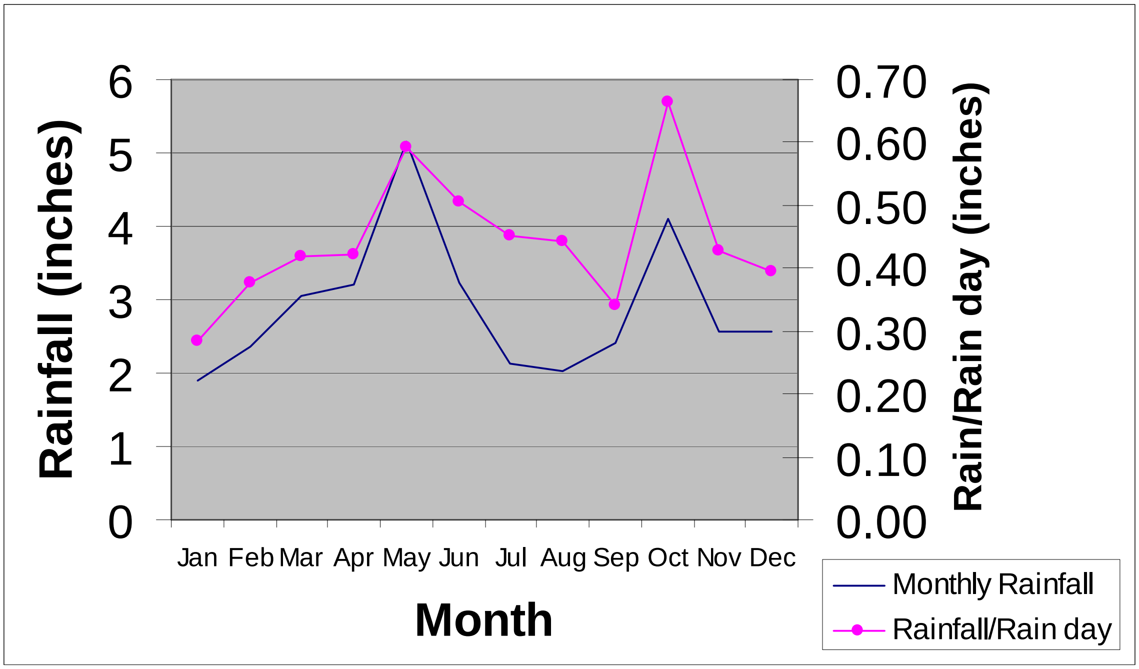


Figure 4.37 Ft.Worth Rainfall. Average rainfall per month (period of record - 30 years) and average rainfall intensity per day. Note: Separate scales are used for each plot. (National Weather Service, 2003)

Rowe led a study in 2002 at Michigan State University in East Lansing, Michigan to determine the effects of slope, substrate depth, and vegetation on storm water runoff (Rowe et al., 2003:6). In one aspect of the study, three different roof types were compared – a conventional roof covered with 2 cm gravel ballast, an extensive vegetated roof approximately 4.5 cm in depth, and a similar extensive roof, 4.5 cm in depth, with growing media but no vegetation. The tests were performed on three platforms measuring 8’ x 8’ with a 2% slope. The platforms faced south for maximum sun exposure. The platforms were divided into 3 sections that were 8 feet long as shown in Figure 4.38. One of each of three roof types was installed in each of the three sections. A collection apparatus was placed under each roof type to determine runoff volume. The objective of the test was to determine the water retention capabilities of each roof type.

Figure 4.38 Divided Test Platform. A divided model-scale platform used to quantify differences in storm water runoff between roof types. (VanWoert et al., 2003)

Figure 4.39 shows the difference in runoff volumes between the three roof types during a 10 mm rain event. There is a significant difference in runoff volumes from a conventional roof and a vegetated roof. The time delay between the beginning of the rainfall event and the time that runoff begins to leave the roof is also noticeable. For this particular event water continued to exit the green roof three hours after water ceased to flow from the conventional roof as shown in Figure 4.39. The time delay validates the reports of slower flow rates of storm water runoff from a green roof as opposed to a conventional roof. The slower flow rates reduce the stress on urban storm sewers.

The study was conducted over a six week period from September 10, 2002 through October 22, 2003. Over the length of the study, only a very small percentage of runoff exited the vegetated or the media only roof as seen in Figure 4.40. During weeks 1 and 3 there was not enough rainfall to register runoff from any of the roofs. Week 4 had the most rainfall with 17 mm total. During that week only 2 mm of runoff was

collected - 12% of the rainfall. This six week study highlights the ability of green roofs to significantly reduce storm water runoff during moderate rainfall events.

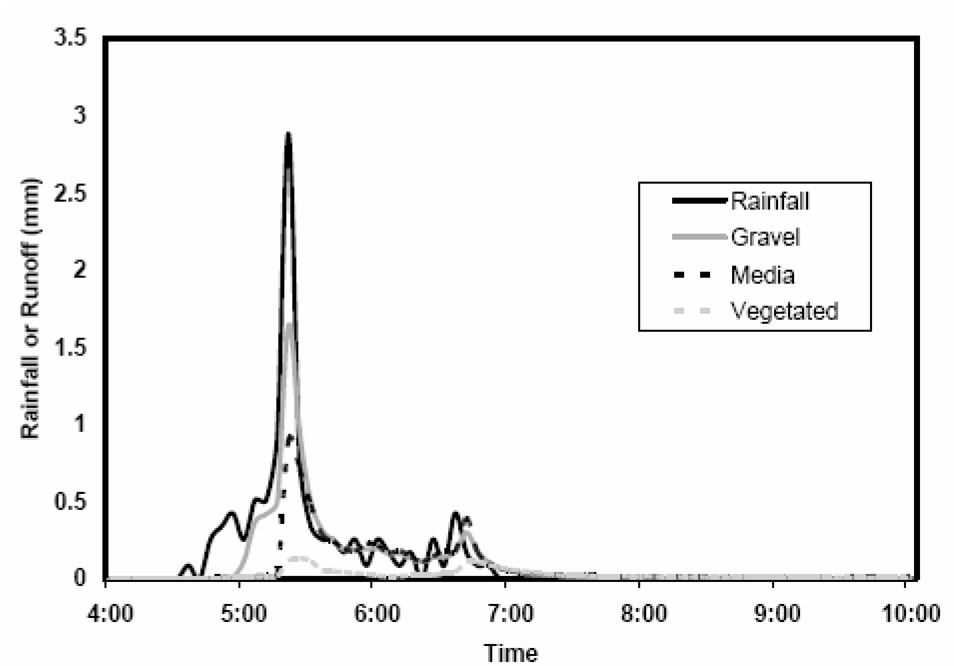


Figure 4.39 Measured Runoff. Representative hydrograph of a 10 mm rainfall event on three different roof types. (Rowe et al., 2003:6)

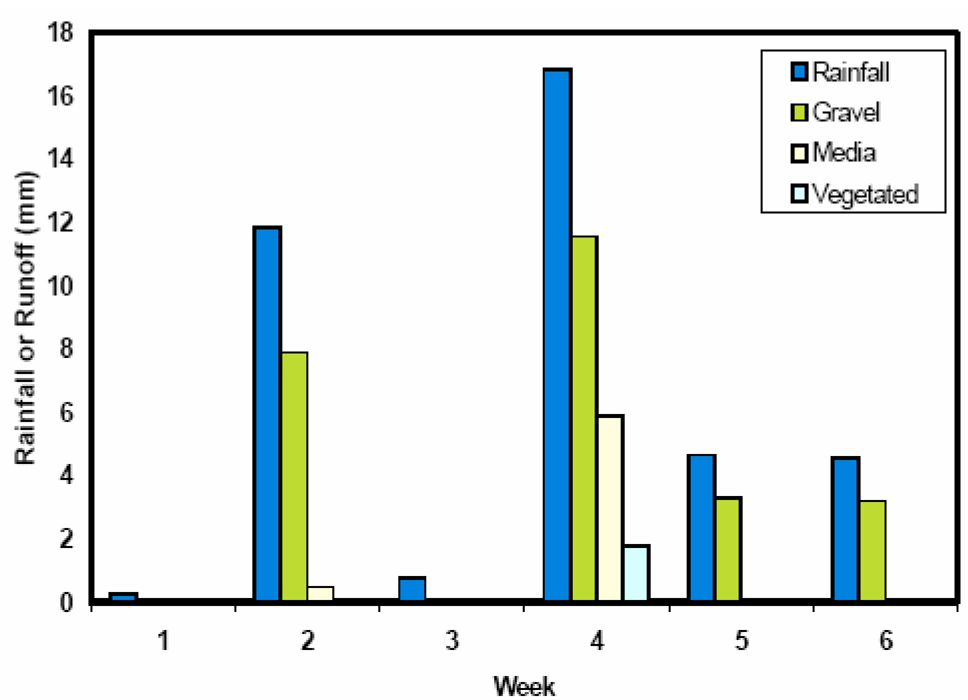


Figure 4.40 Rainfall and Runoff. Weekly rainfall and runoff totals for a six-week period from September 10, 2002, through October 22, 2003 (Rowe et al., 2003:7).

The second aspect of Rowe's study shows the effects of roof slope and substrate depth on runoff. Twelve platforms measuring 8' x 8' were used. The study compared substrate depths (2.5 cm, 4.0 cm, and 6.0 cm) and slope (2% and 6.5%) and their effect on water retention with the platform set-up shown in Figure 4.41. Three platforms were constructed with 6 cm of substrate depth at a 6.5% slope. Three platforms were constructed with 4.0 cm of substrate depth at 6.5% slope. Six platforms had a slope of 2%. Three of these platforms had 4 cm of substrate and the other three platforms had 2.5 cm of substrate. All twelve platforms had 100% vegetation coverage.

Figure 4.41 Test Platforms. Model-scale platforms used for evaluating storm water retention. (VanWoert et al., 2003)

During the time period from September 10, 2003 to October 27, 2002 and March 20-28, 2003 there were 24 total rainfall events. There were 7 light rains (<2 mm), 9 medium rains (2 to 4 mm), and 8 heavy rains (>4 mm). The data relating to the reduced level of runoff is shown in Figure 4.42 and Table 4.5. When the results of all of the

events were combined, the highest retention rate observed in the study was 74% on the platforms with 4 cm of substrate at a 2% slope. The lowest retention rate was 69% occurring on the platforms with 4 cm of substrate and 6.5% slope. It is clear that slope and substrate depth among other things, are factors in storm water retention. The small 5% difference between the best case and worst case shows that all green roofs tested demonstrate significant water retention capabilities.

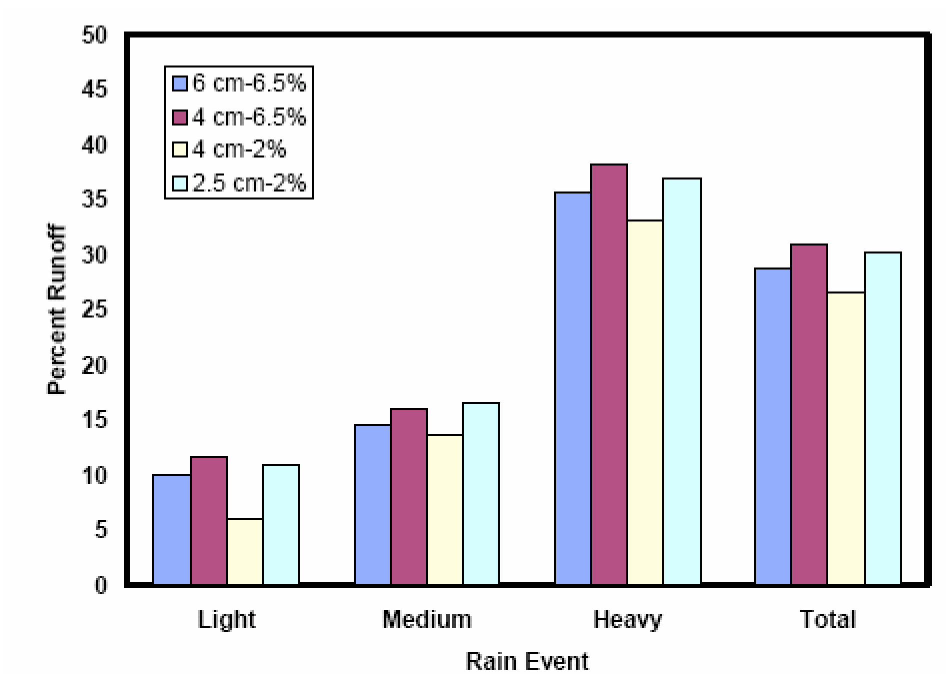


Figure 4.42 Runoff. Influence of roof slope and substrate depth on storm water runoff. The highest retention of water was observed for a platform with 4 cm of substrate and a 2% slope. (Rowe et al., 2003:8)

Table 4.5 Storm Water Retention. Mean storm water retention percentages for categorized rainfall events (Light, <2mm; Medium, 2 – 6mm; Heavy, >6mm). Means within same column followed by a different letter are significantly different (Tukey, p<0.05). (VanWoert et al., 2003)

		Light	**Medium**	**Heavy**
2% Slope	**2.5 cm**	95.93a	87.73a	68.35a
	4 cm	98.18b	90.14b	71.96a
6.5% Slope	**4 cm**	96.29a	88.78a	65.14a
	6 cm	96.84a	89.81a	68.27a

4.3 Assumptions and Calculations

To effectively calculate a net present value for the two roofing systems being compared, several assumptions and calculations were made. Those assumptions and calculations are presented subsequently with information used in the net present value calculations.

4.3.1 Rainfall/Retention Calculations

Climatic data collected for the Dallas/Ft. Worth (DFW) area and posted on the National Weather Service website were used in calculations and in various design considerations. An overall summary of the information can be seen in Appendix B.

From the National Weather Service Tables mentioned above, water retention calculations were developed and are shown in Appendix B. The tables indicated that over the last 30 years the average annual rainfall for the DFW area is 34.73 inches and equates to a 2.9 inch average monthly rainfall. With a 2.9 inch monthly rainfall, the roof on Building 15, which is 101,430 ft^2, would receive 183,352 gallons of rain each month. With an average retention rate of 75% (Perry, 2003a; Scholz-Barth,2001:4), the green roof will retain 137,514 gallons of water that would become storm water runoff if it landed on a conventional roof. Over the course of an average year, Building 15's roof would receive 2,200,224 gallons of water, and 1,641,168 gallons would be used by the green roof rather than becoming storm water runoff.

For design purposes, the monthly rainfall extremes were considered. The month of May has the highest average monthly rainfall at 5.15 inches, and January has the lowest average monthly rainfall at 1.90 inches. Even though May has the highest monthly rainfall, the rain events are somewhat dispersed. On average, less than two days

in May yield more than an inch of rain. With the rain showers being dispersed, the green roof will be able to maintain a high level of water retention. In January, when the area average rainfall is only 1.90 inches of rainfall, the plants are typically in their dormant stage and do not require a great deal of water.

4.3.2 Energy Cost Savings

Energy savings were calculated as a percentage of the overall cooling cost estimated by facility engineers for LM. Estimated cooling costs were used because LM does not have a means of measuring the electricity used specifically for cooling. LM engineers provided the cooling cost estimates based on cooling demands and the energy consumption rates of heating, ventilation, and air conditioning (HVAC) equipment specific to each facility.

While the National Research Council's studies led by Liu and Baskaran (2003) showed that energy usage can be reduced by as much as 75% based solely on heat flow through the roof, a much more conservative percentage was chosen for the cost analysis. Other factors such as heat flow through walls, windows, and doors, heat produced by computers, office equipment, and large numbers of employees add to heat loads. Other green roof experts report actual energy savings for a facility are likely to be approximately 25% (Scholz-Barth, 2001:4; Perry, 2003a). The most conservative estimates predict a 5% cooling savings (Russell, 2003). Therefore, in the LCEA, the savings due to cooling reductions will range from 5% to 25% of the annual cooling cost for Building 15. In the net present value calculations, three cost comparisons will be

made; conservative, mid-range, and optimum dollar values will be evaluated. The annual cooling cost for Building 15 is estimated to be $50,000 (Harrison, 2003).

4.3.3 Maintenance

Maintenance on the two roofing systems considered in the analysis is quite different. On an asphalt BUR, maintenance activities encompass minor repairs. Patching areas that are beginning to crack or repairing leaks around roof penetrations is routine maintenance on a BUR. Occasionally a new application of felt and asphalt may be needed in certain areas of the roof. BURs do not typically follow an exact maintenance timeline. Many times maintenance is done on an “as needed” basis. The quality of materials used in the roof installation, the skill of the roofing contractor during installation, and exposure to the weather are just a few factors that affect roof performance and maintenance. This maintenance is typically minimal when the roof is new. As the BUR approaches the end of its useful life, maintenance costs increase exponentially (Harrison, 2003).

After talking with the facility engineers at AFP4, the most accurate way to formulate maintenance costs for the analysis was to take them from a cost plot. Maintenance costs seem to follow an exponential distribution starting at $0 when the roof is new and increasing to approximately $.50/ft^2 at the end of the roof life (Harrison, 2003). In the analysis for Building 15 the final maintenance cost will be $50,000/year as predicted by LM engineers (Harrison, 2003). The exponential curve used to derive maintenance costs for the asphalt BUR is shown in Figure 4.43. The values used in the cost evaluation are assumed to be the total expenditures from the preceding year. No

maintenance costs were tallied in the 15th year of the roof life because it is not likely LM would perform maintenance in the year before the roof is replaced.

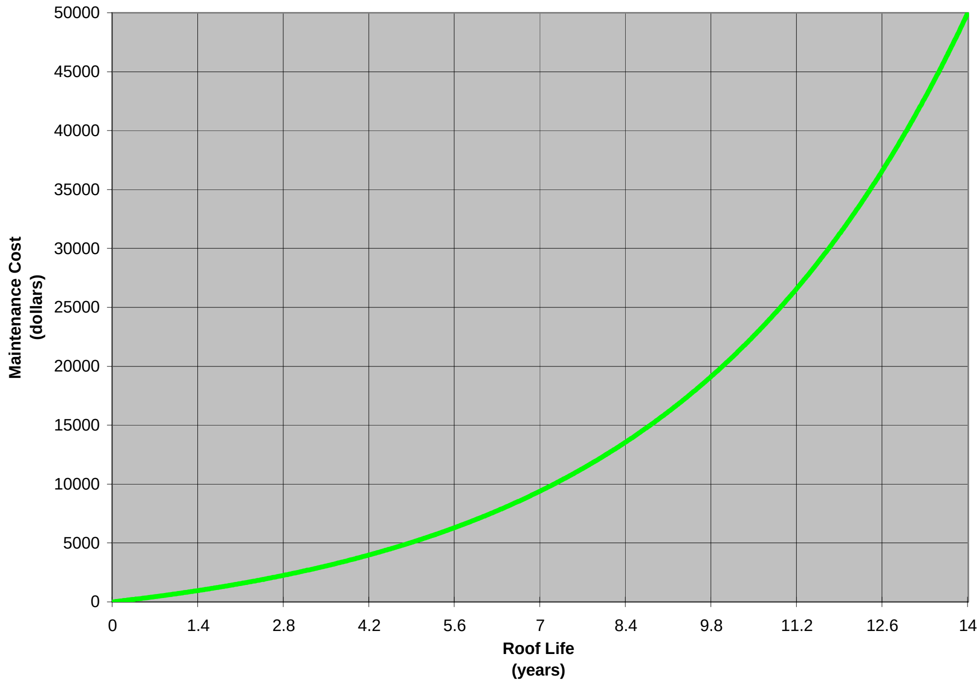


Figure 4.43 Maintenance Costs. Exponential distribution depicting the estimated rise in maintenance cost on an asphalt BUR. Rho is -4.8. Range of maintenance costs is \$0 – \$50,000 over a roof life of 15 years. No maintenance likely in last year before replacement. (Weir, 2003; Harrison, 2003)

Vegetated roofs have minimal maintenance requirements after the roof is established. Maintenance also depends on the type of green roof installed. Some roofs receive an annual application of fertilizer, and some are irrigated on an as needed basis. The fertilizer, as recommended by a green roof expert from Xeroflor America, should be applied at a rate of approximately 0.035 oz/ft^2 which typically costs approximately 0.22 cents/ft^2, or 2.4 cents/m^2, for an annual application (Monterusso, 2003). The annual cost for fertilizer for Building 15 would be less than \$225 and would require approximately 2 man-hours to apply (Monterusso, 2003). The cost of irrigating is negligible. Irrigation would only be needed during droughts, and water costs are minimal. A visual inspection

should be done every month, especially the first two years, to determine if irrigation or fertilizer is needed (Monterusso, 2003). After the vegetation is established, maintenance expenses on a vegetated roof are minimal (Perry, 2003). Man-hours for inspections are anticipated to be approximately one hour each month at a rate of $20/hr (Harrison, 2003). The labor cost for the fertilizer application and the monthly inspections would be $280. A sum of $500/yr should be budgeted to cover annual maintenance on the green roof.

4.3.4 Applicability

The overall green roof design developed for Building 15 at AFP4 in Ft. Worth, Texas could be installed on any other similar building in a similar climate provided the roof had adequate structural support. The green roof design took into account the high summertime temperatures and the average annual rainfall. Water retention capabilities and an irrigation system were included to ensure adequate moisture was available for the plants during the extreme summer months.

4.4 Cost Estimates

4.4.1 Building 15 Green Roof Cost Estimate

The preliminary design and cost estimate for the green roof to be installed on Building 15 were developed by Michael D. Perry, Hon. AIA, president Building Logics in Virginia Beach, Virginia. Mr. Perry is a leader in the green roof industry in the United States and has been involved with vegetated roofing projects and educational initiatives around the world. The design and cost estimate was provided by an expert in the field to obtain the best possible data for use in the net present value calculation.

Mr. Perry performed a site visit to AFP4 in June 2003. The site visit was also attended by the author. He gave an informative presentation about vegetated roofing technology to the LM facility engineers. During the visit, he was able to observe the roofing conditions and the type of equipment installed on the roof. The LM engineers provided Mr. Perry with roof drawings and digital pictures of the roof showing installed equipment, drains, and other details needed to develop a roof design.

In developing the preliminary design so that a cost estimate could be formulated, Mr. Perry took the extreme environmental conditions of Ft. Worth into consideration. The climate was a factor in determining the type of components needed in the roofing system. The high temperatures and seasonally arid conditions create the need for additional water retention components for the plants and also influenced the decision about the types of plants selected for use.

The installation of the green roof would involve several layers. Insulation would be fastened directly to the roof deck with mechanical fasteners. Type III asphalt would be used as an adhesive when installing the 0.5" high density fiberboard. The fiberboard would be placed on top of the insulation as a thermal barrier to protect the insulation when the base ply of the waterproofing membrane, Famobit P4, is installed. The membrane is applied by heating the bottom with a torch causing it to adhere to the fiberboard. Without the fiberboard, the flame from the torch would damage the insulation when heating the membrane. The top ply of the membrane, Famogreen Ret CU-P4, is then torch-applied to the base ply. The Famobit P4 and the Famogreen Ret CU-P4 combine to form the waterproofing membrane which has inherent root protection as well as water retention capabilities. A filter fabric is placed over the Famogreen Ret to

prevent particles from clogging the drainage pathways that develop when the gel crystals absorb water. The gel crystals are held in square sections by a fabric that is glued to the membrane. As the crystals absorb water, they expand. The spaces between the sections of crystals become the drainage pathways, allowing excess water to leave the roof. The growing medium would be installed above the filter fabric and plant plugs ($2/ft^2$) would be planted in the growing medium. The growing medium would be a blend of mineral rocks, sand, and topsoil. Plugs were chosen because they are more affordable and more accessible in the United States. However, plant plugs require more maintenance initially until they can establish themselves. During the first two years, small amounts of fertilizer may be needed and the irrigation system would be used. After two years the plants should provide 100% coverage of the roof. After the plants cover the roof, maintenance requirements will be minimal to nonexistent. The roof will provide excellent water retention benefits as well as a significant reduction in cooling costs.

The installation cost estimate, shown in Appendix B, encompasses all aspects of the job to replace the Building 15 roof – insurance, bonds, demolition and disposal of the old roof, installation of the new roof, warranty, taxes, as well as overhead and profit. The total initial price for the roof project is \$1,072,083, or $\$10.57/ft^2$.

4.4.2 Building 15 Asphalt Built Up Roof Cost Estimate

The most conservative cost estimate provided by the LM facility engineers at AFP4 is part of a roofing study that was initiated and completed in 2001 to determine the capital investment cost that would be needed to bring the roofing on 17 different facilities up to standards. The estimate is to remove the existing roof system and replace it with a Johns-Manville 4 ply, type six, asphalt and gravel roof system. This type of roofing is of

moderate quality and would likely provide adequate service for 10 – 15 years. The National Roofing Contractors Association has information on studies that show the average life span of an asphalt BUR is 13.6 years. In the studies, over 24,000 roofs were analyzed between 1975 and 1996 (Hoff, 2003). The estimate, shown in Table 4.6, shows the total initial cost for the replacement with an asphalt BUR of the Building 15 roof is \$523,363, or \$5.16/ft^2. This estimate contrasts with the \$6.05 - \$7.60/ft^2 that LM engineers received in bids in early 2003 to replace roofs similar to the one on Building 15 (Mockler, 2003). There may be several reasons for this. The price of \$523,363 was part of an estimate to do 17 facilities, and the total price for all 17 facilities was \$15.4 million. By doing such a large project, the contractor may have been able to improve the estimated cost based on economy of scale. Also, the estimate does not indicate that the roof will have a warranty or the profit that the contractor will make. (The green roof estimate shows a 20% profit as well as a warranty.) Another savings might come from the fact that the contractor would only have mobilization and demobilization costs once to repair roofs on multiple facilities on AFP4.

Table 4.6 Lockheed Martin roof replacement cost.

Building Number	**#15**
Building Roof Rating	12
Labor Costs	$169,148
Expenses	$40,218
Upload and Demo Equipment	$48,461
Insulation and Asphalt Materials	$164,042
Membrane and Metal Materials	$57,570
Miscellaneous Materials	$43,912
Total Budgetary Investment	$523,363

4.5 Life Cycle Economic Analysis

After collecting the cost data for installation, maintenance, and savings for the two roofing systems, life cycle cash flows were determined. Cash flow diagrams (Figures 4.44 and 4.45) provide a visual representation of expenditures and savings over the lives of the roofing systems.

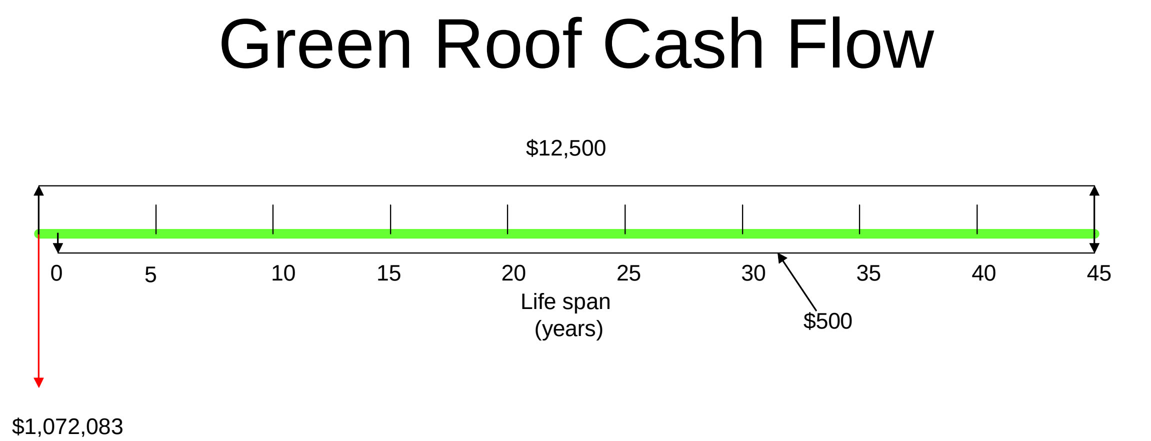


Figure 4.44 Cash Flow Diagram. Cash flows over the 45 year life of a green roof - $500 is paid out yearly in addition to the initial expenditure of $1,072,083. Cooling reductions result in an annual $12,500 savings.

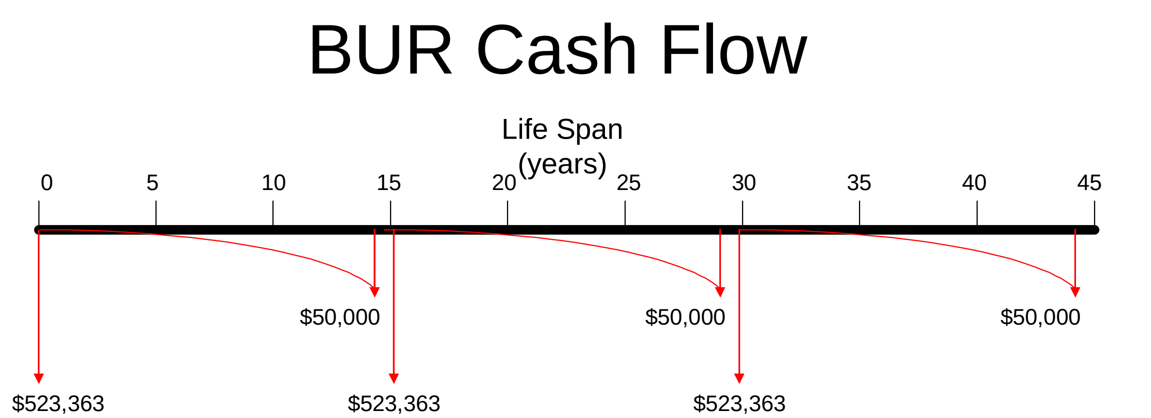


Figure 4.45 Cash Flow Diagram. Cash flows for asphalt BUR over 45 years. Yearly maintenance expenditures range from $0 to $50,000 in addition to the $523,363 installation costs.

To compare the life cycle costs of both roofs, the cash flows for the roofs were calculated and presented as a net present value. To accurately calculate the net present

values for the roofing systems, the alternatives being analyzed have to be compared for an equivalent time period (Fabrycky and Blanchard, 1991:34,89). Although no long term scientific research has been performed to determine the average life span for extensive green roofs, available information indicates that green roofs will last 45 years and longer. Therefore, conventional roofs have to be analyzed over the same time period. Even though the average life of an asphalt BUR is 13.6 years (Hoff, 2003), a conservative life span of 15 years was chosen for the asphalt BUR for the comparison. The 15 year life span for the BUR facilitates a simple comparison to the green roof.

Tables 4.7-4.9 provide the breakout of the costs for each roofing system. The entire detailed cost estimates for the green roof and the asphalt BUR can be seen in Appendix B and Table 4.6, respectively. The installation costs for the roofing systems are broken out differently because they were provided by two different sources. The cost of annual maintenance charges each year during the life of the asphalt BUR and the green roof are also shown. The maintenance values for the BUR are taken from the exponential distribution shown in Figure 4.43 while the annual maintenance values for the green roof total \$500. Annual savings for the green roof range from \$2500 - \$12,500 annually. The savings are calculated as a percentage of the annual cooling cost of \$50,000.

The evaluation to compare the roofs was performed three times using conservative, moderate, and optimal values relative to the green roof. Conservative values were used in the first trial and are shown in Table 4.7. The lowest cost estimate for the installation of the conventional roofing system (\$523,363) and the lowest percentage for cooling savings realized from green roofs (5%) were used in the calculations presenting a bias against the green roof. Using these values, the net present

value for a 45 year green roof is $982,083 compared to a net present value of $2,246,647 for the asphalt BUR over the same period.

In the second trial, mid-range values were used. One of the bid prices that LM

Table 4.7 LCEA summary. Conservative values show the green roof is less than ½ the cost of the BUR.

Conservative Values

	Green Roof	Asphalt BUR
Cost/square foot	$10.57	$5.16
Roof size	101430	101430
Installation Cost	$1,072,083	$523,363
Annual Savings	2,500	0
Avg annual Maintenance	500	a
Life Span	45	15
NPV	982,083	2,246,647

a – maintenance costs found in Table B.3

Table 4.8 LCEA summary. Moderate values show the green roof is 3.3 times more affordable than a BUR.

Moderate Values

	Green Roof	Asphalt BUR
Cost/square foot	$10.57	$6.05
Roof size	101430	101430
Installation Cost	$1,072,083	$613,652
Annual Savings	$7,500	$0
Avg annual Maintenance	$500	a
Life Span	45	15
NPV	$757,083	$2,517,549

a – maintenance cost found in Table B.4

Table 4.9 LCEA summary. Optimal values show the green roof is 5.6 times more affordable than a BUR.

Optimal Values

	Green Roof	Asphalt BUR
Cost/square foot	$10.57	$7.60
Roof size	101430	101430
Installation Cost	$1,072,083	$770,868
Annual Savings	$12,500	$0
Avg annual Maintenance	$500	a
Life Span	45	15
NPV	$532,083	$2,989,198

a – maintenance cost found in Table B.5

received for replacing asphalt BURs in 2003 ($6.05/ft^2 or $613,652 for installation) was used because it was approximately half way between price per square foot derived from the lowest estimate and the highest bid price. Savings for the green roof were based on a 15% reduction in cooling cost – the mid-range value between the optimal savings of 25% and the minimum value of 5%. The NPV for the green roof was calculated as $757,083 compared to the asphalt BUR NPV of $2,517,549 as shown in Table 4.8.

The optimal values that were used in the third trial were the high end of the bids LM received for roofs similar to that on Building 15 ($7.60/ft^2 or $770,868). The cooling savings were calculated at 25% and were based on the numbers many green roof experts say are reasonable to expect from an average extensive green roof. These values bias for the green roof and are shown in Table 4.9. These values resulted in a NPV of $532,083 for the green roof and $2,989,198 for the conventional roof. The optimal values show that the green roof is approximately the $^1/_6$ cost of an asphalt BUR when life cycle costs are considered. Using the most conservative estimates to evaluate the roofing systems, the green roof was more than twice as affordable as the conventional asphalt BUR.

Table 4.10 Comparison of analyses results. Conservative values bias against the green roof while optimal values bias for the green roof.

	Conservative Values	**Moderate Values**	**Optimal Values**
Green Roof	$983,083	$757,083	$532,083
Asphalt BUR	$2,246,647	$2,517,549	$2,989,198
Cost Ratio: Asphalt BUR/Green roof	2.3	3.3	5.6

A tabular comparison of the cost analyses is shown in table 4.10. In all three calculations, conservative, moderate, and optimal, the green roof appears to be more

affordable when the life cycle costs are considered. Other positive impacts of a green roof such as storm water retention, improved microclimate, reduction of the urban heat island effect, acoustical benefits, and the creation of wildlife habitat were not equated to a dollar value and were not a part of the LCEA. Even without considering the numerous qualitative environmental benefits in conjunction with the LCEA results, green roofing technology appears to be feasible for application at AFP4 as well as other locations around the world. Case studies and site visits indicate that vegetated roofs thrive in multiple climates supporting a vast range of vegetation. The results and observations of this study indicate that vegetated roofs are a cost effective and environmentally sound roofing alternative.

V. Findings and Conclusions

5.1 Introduction

The objective of this research effort was to determine if vegetated roofing, a new, environmentally friendly technology was suitable for Air Force applications, specifically AFP4, Building 15 in Ft. Worth, Texas. All calculated and collected data indicates that a green roof would be well suited for AFP4 and potentially for other bases throughout the United States Air Force. This research effort has provided a better understanding of the features and characteristics of vegetated roofing, its applicability to specific geographical locations, the benefits and disadvantages associated with it, and the life cycle cost of installing this type of roofing system on a facility at AFP4 in Ft. Worth, Texas.

Ultimately, this research effort sought to answer the following questions: 1) Where have green roofs been used successfully in the past and what are the characteristics, benefits, and problems encountered with those roofs? 2) What is a viable green roof design for Building 15 at AFP4 based on successful green roof applications and the recommendations of experts in the green roof industry? 3) What is the life cycle cost of a green roof and the conventional roofing system that would be used at AFP4? 4) What are the anticipated characteristics, benefits, and maintenance requirements for a green roof at AFP4?

5.2 Characteristics, Benefits, and Disadvantages

Green roofs have been used successfully throughout the industrialized world. Europe has the largest concentration of vegetated roofs, and the popularity of this roofing system is spreading. Green roofs are continuing to grow in popularity in Europe as well

as parts of Asia and North America. Observation of roofs in Germany and the United States revealed that there are many similarities between green roofs, and there are some differences as well.

There are key components to current green roofs systems. Vegetated roofs require a waterproofing membrane, root barrier, drainage mechanism, filter fabric, growing medium, and vegetation. Climatic conditions may dictate the need for additional components such as insulation, water retention materials to provide moisture for the plants during dry periods, and possibly a wind blanket to prevent erosion until the plants are able to establish themselves. These components work together as a roofing system to provide many economic and environmental benefits.

The positive benefits cover a broad environmental spectrum. One of the major benefits is a large reduction in storm water runoff, which reduces soil erosion, lessens the burdens on storm sewers and waste water treatment plants, and reduces water pollution in local bodies of water. Green roofs are known to provide thermal benefits that result in a 5 - 25% cooling cost reduction and can reduce heating cost as well. Vegetated roofs extend the life of the roofing membrane by two to three times that of conventional roofs; extending the roof life saves money in replacement costs and prevents large amounts of waste roofing material from entering landfills. The urban heat island effect is lessened when green roofs are used in metropolitan areas because the vegetation absorbs less heat and therefore, does not re-radiate heat into the atmosphere. The ambient air temperature can be lessened by several degrees requiring less energy for cooling and also reduces smog. Green roofs improve the microclimate by filtering dust particles out of the air, producing oxygen, and consuming carbon dioxide while becoming a wildlife habitat – a

sign of environmental health. Green roofs may also reduce the transfer of outside noises into buildings. Vegetated roofs provide these benefits while simultaneously improving the appearance of the overall landscape.

The drawbacks to vegetated roofing typically center on the higher upfront costs – typically green roofs costs are 30 – 40% higher than conventional asphalt built up roofing. The green roofing industry is in its infancy in the U.S. and obtaining the materials for a large roof can require substantial lead-time, however, as the industry grows these problems are diminishing. One other drawback with green roofs is they require more care during the first year or two after installation. The vegetation has to be observed closely until the plants develop a mature root system and provide 100% coverage of the roof.

A preliminary green roof design and cost estimate were developed for Building 15 at AFP4 based upon successful green roof applications in locations around the world. The design was adapted to suit the climatic conditions of Ft. Worth Texas, where AFP4 is located. The roof design included insulation, high density fiberboard, a waterproofing membrane, a filter cloth, a growing medium, and sedums as a choice of plant materials. The life cycle cost, as a NPV, was found to be $^1/_2$ - $^1/_6$ the cost of the built up asphalt roof.

5.3 Limitations

Because vegetated roofing technology is in its infancy in the U.S., there has been very little formal research on green roofs in this country. Much of the information that is known about vegetated roofing comes from Europe, specifically Germany and much of that information is from empirical observation. Questions arise as to whether vegetated

roofing will perform the same in all parts of the U.S. with its climatic diversity. However, there are successful roofs in many parts of the country as well as in Canada. The performance of these roofs seems to indicate vegetated roofs will perform well in all parts of the U.S. with slight variations between them.

Several universities and businesses around the country have begun to perform research on specific aspects of vegetated roofing. A committee from the American Society for Testing and Materials is currently assembling drafts of future vegetated roofing standards (Velasquez, 2003) adding uniformity and predictability to this emerging industry. This research and certification will likely reveal how components can be adjusted to maximize certain aspects of roofing performance. As this research is replicated and documented, many assertions and assumptions currently made when designing a green roof will become documented facts or be adjusted to more accurately predict roof performance. Construction of vegetated roofing will become a more standardized process. The information from these research efforts would likely improve the quality and performance of roofs translating into improved cost figures.

Additionally, this research examined only one facility, Building 15 at AFP4. This building was located at one specific location and only one specific roof design was selected for cost comparison. Obviously, if another roof design was chosen or the roof was being replaced at a different climatic location, life cycle costs and net present values could be substantially different. However, the process used during this research effort can be easily applied to any building at any location.

5.4 Future Research

The scope of this research effort focused on the comparison of vegetated roofing and asphalt built up roofing. Further investigations could be performed to determine how the performance of vegetated roofing compares to metal roofing, single ply membranes, shingles, or other types of roofing. Each type of roofing has different qualities and performance characteristics as well as different costs and should be evaluated.

In future comparisons, researchers may be able to determine a valid method to assign a dollar value to some of the environmental benefits; perhaps by using one or several various cost models. Some of these environmental benefits, such as the reduction of air and water pollution, have the potential to save the Air Force money. Reductions in pollution may help the Air Force avoid fines for exceeding regulatory limits. These air and water pollution reductions may also prevent future restoration efforts by preventing environmental degradation. Models could be developed or existing models used to determine the positive impact of installing green roofs on DoD facilities in large metropolitan areas where the urban heat island effect, smog, and surface water pollution are persistent problems. The value of qualitative benefits, such as aesthetics, could be valuated and incorporated into roof comparisons. It has been suggested that people in offices overlooking lower level green roofs may experience improved morale and productivity, and patients in hospital rooms overlooking green roofs experience faster medical recoveries. If future research can adequately incorporate these additional benefits into comparisons, green roofs may prove to be even more valuable than shown during the current research.

5.5 Conclusions

During the entire research effort, literature searches, site evaluations, and cost comparisons, no information obtained or observed illustrated any significant problems with vegetated roofing. When an adequate design is developed and the roof is installed properly, vegetated roofing is a feasible roofing alternative. Using even the most conservative cost data over the life of the roof, the cost analysis revealed that a vegetated roof is less than half the cost of an asphalt BUR. The life cycle cost comparison in conjunction with the environmental benefits provided by vegetated roofing definitively shows vegetated roofing is feasible for Building 15 at AFP4.

Appendix A: Case Study Questions

The following questions were used during site visits.

U.S. Green Roof Questions

1a. How was this roof constructed?

1b. What types of building materials were used? Costs? Brand? Application method? Failure modes or degradation issues?

– Soil mix
  --Will soil have to be added in the future due to erosion, degradation, etc?

– Type of waterproofing membrane?

– Root barrier?

– Insulation?

– Protective Mat?

– Drainage Layer?

– Filter Layer?

– Plants?
  -- How are plants affected by moisture, temperatures – winter vs. summer, wind, minimum or maximum events, hail?

2. What is the predicted life span of this roof? When do you anticipate having to replace?

3a. What are the predicted/budgeted average annual maintenance costs?

3b. What types of maintenance activities will need to be performed?

4a. What is the average annual heating/cooling cost of the building? How are heating/cooling costs quantified? Units? What portion of energy goes to heating?

4b. How much space is being heated/cooled?

4c. What are the cost savings compared to a facility with a traditional roof?

5. Has the roof had any leaks?

6. Have any predictions been made to predict if the roof will help moderate storm events?

7a. What is the dry roof weight per square foot?

7b. What is the saturated roof weight per square foot?

8. Have there been any noted water quality improvements in nearby lakes or streams? Or have you taken any water quality measurements on water coming from the roof?

9. What are the exterior roof temps when the outside temps are 30, 60, and 90 degrees? Difference between interior and exterior roof surface?

10. Have there been any problems with birds or other animals inhabiting the roof?

11. Have there been any problems with weeds, molds, pests?

12. Was a leak detection system installed? Type? Brand? Added Costs? Life Expectancy?

13. What is the difference in runoff volumes before and after the green roof?

14. Any other noted benefits/drawbacks?

German Green Roof Questions

1. How was this roof constructed – depth of soil, type of plants, etc?
membrane:
    brand or type
    application method

root barrier:
    brand or type
    application method

insulation:
    brand or type
    application method

drainage layer:
    brand or type
    application method

substrate:
- type of mix
- depth of substrate
- application method

Plants:
- brand
- application method (mats, plugs, seeding)

2. How old is the roof?

3. What are the average annual maintenance costs?

3b. What types of maintenance activities need to be performed?

4a. What is the average annual heating/cooling cost of the building?

4b. How much space is being heated/cooled?

4c. What are the cost savings compared to a facility with a traditional roof?

5. Have there been any noted water quality improvements in nearby lakes or streams? Or have you taken any water quality measurements on water coming from the roof?

6. What are the exterior/interior roof temps when the outside temps are 30, 60, and 90^{o}F?

7. Have there been any problems with birds or other animals inhabiting the roof?

8. Have there been any problems with weeds, molds, pests?

9. Was a leak detection system installed? Type? Brand? Added Costs? Life Expectancy?

10. What is the difference in runoff volumes before and after the green roof?

11. Any other noted benefits/drawbacks?

AFP4 Questions

1a. How was this roof constructed?

1b. What types of building materials were used?

2. What is the predicted life span of this roof? When do you anticipate having to replace?

3a. What are the predicted/budgeted average annual maintenance costs?

3b. What types of maintenance activities will need to be performed?

4a. What is the average annual heating/cooling cost of the building?

5. How much space is being heated/cooled?

6. Has the roof had any leaks?

7. What is the roof weight per square foot?

8. Have there been any noted water quality measurements in nearby lakes or streams? Or have you taken any water quality measurements on water coming from the roof?

9. What are the exterior roof temps when the outside temps are 30, 60, and 90 degrees?

10. Any other noted benefits/drawbacks of the roof?

11. What is the structural makeup of the existing roof?

12. What type of insulation is used on the current roof? R-value?

13. How many square feet are going to be replaced with this project?

14. Who would I contact with additional questions?

15. What is the average annual rainfall per month?

16. What are the average monthly temperatures?

17. What are the estimated costs to replace roofs with traditional means?

18. Will the roof deck be replaced?

Appendix B: Calculations and Data Tables

The following conversions and tabular data were used during cost and storm water calculations.

Conversions

1 ft^3 = 7.48 gal   1 in^3 = .0043 gal   1 g H_20 = 1 cm^3

1 oz = 28.35 grams   1 gal = 128 fluid oz.   1 lb = 16 oz.

1 m^2 = 10.76 ft^2 1kg = 2.2 lbs.

Storm Water Calculations:

Equation B-1 shows the average monthly rainfall in Ft. Worth.

2.9 in * (1 ft/12 in) * 101,430 ft^2 * (7.48 gal/1 ft^3) = 183,352 gallons   (B-1)

Equation B-2 shows the average amount of rainfall retained in one month by the building 15 green roof.

182,352 gallons * .75 = 137,514 gallons   (B-2)

Table B.1

DFW Annual Summary of Normal, Means, and Extremes

Temperature (°F)

	POR	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	YEAR
Normal Daily Maximum	30	54.1	60.1	68.3	75.9	83.2	91.1	95.4	94.8	87.7	77.9	65.1	56.5	75.8
Mean Daily Maximum	51	54.6	57.9	67.5	76.2	83.2	91.6	96.0	95.6	88.5	78.6	66.2	57.9	76.3
Highest Daily Maximum Year of Occurrence	45	88° 1969	95° 1996	96° 1991	95° 1990	103° 1985	113° 1980	110° 1998	108° 1964	108° 1998	102° 1979	89° 1989	88° 1955	113° Jun 1980
Mean of Extreme Maximums	51	76.2	80.2	85.4	89.2	94.1	99.0	102.7	103.1	98.6	92.4	82.9	77.4	90.1
Normal Daily Minimum	30	34.0	38.7	46.4	54.0	63.0	70.7	74.6	74.0	67.2	56.4	45.1	36.8	55.1
Mean Daily Minimum	51	33.7	38.2	45.2	54.3	63.0	70.8	74.7	74.0	67.0	56.2	44.7	37.0	54.9
Lowest Daily Minimum Year of Occurrence	56	4° 1964	7° 1985	15° 1980	29° 1989	41° 1978	51° 1964	59° 1972	56° 1967	43° 1984	29° 1993	20° 1959	-1° 1989	-1° Dec 1989
Mean of Extreme Minimums	51	16.0	21.1	27.4	37.5	49.5	60.3	67.5	65.6	52.6	40.3	28.6	20.4	40.6
Normal Dry Bulb	30	44.1	49.4	57.4	65.0	73.1	80.9	85.0	84.4	77.5	67.2	56.4	45.1	65.5
Mean Dry Bulb	51	44.2	48.9	56.3	65.3	73.0	81.2	85.3	84.9	77.7	67.3	55.3	47.4	65.6
Mean Wet Bulb	15	40.2	44.3	50.5	57.4	66.4	72.2	73.8	73.1	68.3	59.7	49.8	42.7	58.2
Mean Dew Point	15	34.0	37.5	43.6	51.0	62.1	68.1	68.5	67.6	63.0	54.2	44.0	37.0	52.6

		POR	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	YEAR
Normal Number Days with...	Maximum >89°	30	0.0	0.0	0.2	1.0	4.5	19.5	27.5	26.8	14.4	3.1	0.0	0.0	97.0
	Maximum <33°	30	1.9	0.7	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.9	3.6
	Minimum <33°	30	15.7	9.3	2.8	0.2	0.0	0.0	0.0	0.0	0.0	*	2.3	10.7	41.0
	Minimum <1°	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	*	0.0

Degree Days

		POR	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	YEAR
Normal	Heating	30	650	448	248	74	13	0	0	0	2	52	312	571	2370
	Cooling	30	2	11	10	72	265	478	621	601	376	118	15	2	2571

Relative Humidity (%)

	POR	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	YEAR
Normal	30	68	66	64	65	70	66	60	60	66	66	67	68	66
Hour 06 LST	30	72	72	69	72	78	74	67	66	74	73	74	73	72
Hour 12 LST	30	79	80	79	82	87	85	80	80	84	82	81	79	82
Hour 18 LST	30	60	58	56	56	59	55	49	49	55	54	56	59	56
Hour 24 LST	30	57	54	50	52	56	50	44	44	52	54	58	59	52

Weather

		POR	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	YEAR
Number of Days with...	Heavy Fog (Vsby <1/4 Mi)	45	2.5	1.5	1.0	0.6	0.3	0.1	0.0	0.0	0.1	0.8	1.5	2.5	10.9
	Thunderstorms	45	1.3	1.8	4.4	5.9	7.4	6.3	4.7	4.4	3.3	3.0	2.0	1.1	45.6

Sky Cover

		POR	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	YEAR
Sunrise-Sunset (Oktas)		1			4.0		3.2							4.8	
Midnight-Midnight (Oktas)		1			4.0										
Number of Days with...	Clear	1	2.0	6.0	15.0		10.0	11.0							
	Partly Cloudy	1		2.0			4.0	8.0							
	Cloudy	1	2.0		7.0		6.0	2.0							

Pressure ("Hg)

		POR	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	YEAR
Mean	Station Pressure	26	29.49	29.49	29.40	29.30	29.30	29.30	29.44	29.40	29.39	29.40	29.40	29.50	29.40
	Sea-Level Pressure	15	30.14	30.08	30.01	29.93	29.90	29.91	29.96	29.96	29.98	30.04	30.08	30.13	30.01

Wind (MPH)

	POR	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	YEAR
Mean Speed	45	11.0	11.7	12.7	12.4	11.1	10.6	10.0	9.1	9.5	9.9	11.0	11.1	10.8
Prevailing Direction	2	020°	010°	180°	340°	180°	180°	180°	190°	180°	180°	160°	340°	180°
Maximum 2-Minute Speed Direction Year of Occurrence	3	41 290° 1996	36 270° 1997	39 170° 1998	38 340° 1997	43 340° 1998	47 320° 1996	34 140° 1997	47 330° 1996	33 240° 1996	41 310° 1998	39 300° 1998	39 250° 1997	47 330° Aug 1996
Maximum 5-Second Speed Direction Year of Occurrence	3	51 190° 1996	44 270° 1997	51 170° 1998	45 190° 1996	49 250° 1998	57 340° 1996	40 300° 1997	47 340° 1996	39 240° 1996	48 190° 1996	47 300° 1998	47 260° 1997	57 340° Jun 1996

Rain (in.)

	POR	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	YEAR
Normal	30	1.90	2.37	3.06	3.20	5.15	3.23	2.12	2.03	2.42	4.11	2.57	2.57	34.73
Monthly Maximum Year of Occurrence	45	5.07 1998	7.40 1997	6.69 1995	12.19 1957	13.66 1982	8.75 1989	11.13 1973	6.85 1970	9.52 1964	14.18 1981	6.23 1964	8.75 1991	14.18 Oct 1981
Minimum Monthly Year of Occurrence	45	T 1986	0.15 1963	0.10 1972	0.11 1987	0.95 1996	0.40 1964	0 1993	T 1980	0.09 1984	T 1975	0.20 1970	0.17 1981	0 Jul 1993
Max in 24 hours Year of Occurrence	45	3.15 1998	4.06 1965	4.39 1977	4.55 1957	5.34 1989	3.15 1989	3.76 1975	4.05 1976	4.76 1965	5.91 1959	2.83 1964	4.22 1991	5.91 Oct 1959
Number of Days with... Precipitation > Tr.	30	6.7	6.3	7.3	7.6	8.7	6.4	4.7	4.6	7.1	6.2	6.0	6.5	78.1
Number of Days with... Precipitation > 0.99	30	0.3	0.5	0.7	1.2	1.4	0.9	0.7	0.8	1.1	1.4	0.6	0.4	10.0

Snow (in.)

	POR	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	YEAR
Normal	30	1.4	1.0	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.3	3.1
Maximum Monthly Year of Occurrence	43	12.1 1964	13.5 1978	2.5 1962	T 1995	T 1995	0.0	0.0	0.0	0.0	T 1993	5.0 1976	2.6 1963	13.5 Feb 1978
Maximum in 24 Hours Year of Occurrence	43	12.1 1964	7.5 1978	2.5 1962	T 1995	T 1995	0.0	0.0	0.0	0.0	T 1993	4.8 1976	2.5 1963	12.1 Jan 1964
Maximum snow Depth Year of Occurrence	48	6 1964	8 1978	2 1971	0	0	0	0	0	0	0	3 1976	2 1983	8 Feb 1978
Number of Days with Snowfall Greater than 1 inch	30	0.5	0.4	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.*	0.1	1.1

Lat: 32° 53'N Long: 97° 02'W Elev (Ground): 551 Feet

(National Weather Service, 2003)

Table B.2

Green Roof Cost Estimate

3213 Virginia Beach Boulevard
Virginia Beach, VA 23452
Telephone: (757) 431-3170
Fax: (757) 431-3172

Project: Building No. 15
Location: Fort Worth, TX
Contractor: TBD
Architect: TBD
Bid Date: TBD
Project Type: Extensive Green Roof with Tear Off
Total Square Footage: 101,430 Square Feet

Description	Quantity	Material	Labor	Total
General:				
Insurance	LS			$3,000
Bond	LS			3,000
Submittals	LS		500	500
Mobilization:				
Temp Fence	-	-	-	-
Dumpster	250 Tons	-	10,000	10,000
Crane	60 Days	-	15,000	15,000
Scaffolding	120 Days	-	3,000	3,000
Vacuum	-	-	-	-
Abatement	-	-	-	-
Propane	25,000#	8,750	-	8,750
Demolition:				
Remove Equipment	LS	-	4,000	4,000
Remove Flashing	2,500 lft	-	1,250	1,250
Remove Roof	101,430	-	30,429	30,429
Tie-Ins	50	-	3,500	3,500
Miscellaneous	LS	-	10,000	10,000

Installation:				
2.5” ISO Insulation	111,573	52,439	5,070	57,509
Mechanical Fasteners	55,786	2,231	5,070	7,301
0.5” HD Fiberboard	111,573	17,851	5,070	22,921
Type III Asphalt 25 Tons	111,573	3,347	5,070	8,417
Glass Base Sheet (2)	111,573	17,851	5,070	22,921
Base Ply (Famobit P4)	111,573	105,994	5,070	111,064
Top Ply (Famogreen RET CU-P4)	111,573	180,748	5,070	185,818
Flashing Ply (Famobit P4 White)	7,500 sq ft	7,275	5,070	12,345
Treated Wood Blocking	-	-	-	-
Fiberboard Cant	960 lft	96	96	192
Primer	50 Gallon	750	-	750
Asphalt Mastic	500 Gallon	1,750	-	1,750
Elastomeric Mastic	500 Gallon	6,000	-	6,000
Sealant	10 Cases	1,000	-	1,000
6” Glass Mesh	100 Roll	1,500	-	1,500
Scupper	-	-	-	-
Roof Drains	12 Each	2,400	4,800	7,200
Lead Pans	12 Each	840	840	1,680
VTR	10 Each	350	350	700
Counter Flashing	840 lft	840	840	1,680
Coping	640 lft	2,240	2,240	4,480
Curbs	-	-	-	-
Vegetation:				
Filter Cloth	101,430	10,143	-	10,143
Growing Medium 3” Thick	906 cy yds	72,480	10,143	82,623
Plants	195,720	34,251	34,251	68,502
Irrigation	LS	-	20,000	20,000
Perimeter Ballast	18 Tons	1,260	1,575	2,835
Close Out:				
Clean Up	LS		4,000	4,000
Warranty	LS		20,280	20,280
Recapitulation:				
Subtotal		532,386	223,654	756,040
Tax .045		23,957	-	23,957
Overhead				113,406
Subtotal				893,403
Profit .20				178,680
TOTAL:				$1,072,083

(Perry, 2003c)

The spreadsheets below were used to calculate the NPV for the roofing systems. The data used in the spreadsheets is explained in Chapter 4. The spreadsheets used in each evaluation – conservative, moderate, and optimal – are shown.

Table B.3

LCEA spreadsheet - Conservative

Green Roof	
General	$6,500
Mobilization	$36,750
Demolition	$49,179
Installation	$639,331
Close Out	$24,280
Recapitulation	$316,043
Total Installation Cost	$1,072,083
Annual Maintenance	$500
Annual Cooling Cost	$50,000
Cooling Cost Reduction	5%
Annual Savings	$2,500
Life Span (years)	45
NPV =	$982,083.00
-	

Conventional Roof	
Labor Costs	$169,148
Expenses	$40,218
Demolition	$48,461
Insul & Asphalt mat'l	$164,042
Membrane & Metal mat'l	$57,570
Miscellaneous Materials	$43,912
Total Installation Cost	$523,351
Savings	$0
Life Span (years)	15
NPV =	$2,246,649.00

Annual Maint Cost	
Year 1	$659
Year 2	$1,472
Year 3	$2,473
Year 4	$3,706
Year 5	$5,227
Year 6	$7,100
Year 7	$9,408
Year 8	$12,253
Year 9	$15,758
Year 10	$20,077
Year 11	$25,400
Year 12	$31,958
Year 13	$40,041
Year 14	$50,000

Table B.4

LCEA spreadsheet - Moderate

Green Roof	
General	$6,500
Mobilization	$36,750
Demolition	$49,179
Installation	$639,331
Close Out	$24,280
Recapitulation	$316,043
Total Installation Cost	$1,072,083
Annual Maintenance	$500
Annual Cooling Cost	$50,000
Cooling Cost Reduction	15%
Annual Savings	$7,500
Life Span (years)	45
NPV =	$757,083.00

Conventional Roof	
Cost/square foot	$6.05
Roof Size (sf)	101430
Installation Cost	$613,652
Savings	$0
Life Span (years)	15
NPV =	$2,517,550.50

Annual Maint Cost	
Year 1	$659
Year 2	$1,472
Year 3	$2,473
Year 4	$3,706
Year 5	$5,227
Year 6	$7,100
Year 7	$9,408
Year 8	$12,253
Year 9	$15,758
Year 10	$20,077
Year 11	$25,400
Year 12	$31,958
Year 13	$40,041
Year 14	$50,000

Table B.5

LCEA spreadsheet - Optimal

Green Roof	
General	$6,500
Mobilization	$36,750
Demolition	$49,179
Installation	$639,331
Close Out	$24,280
Recapitulation	$316,043
Total Installation Cost	$1,072,083
Annual Maintenance	$500
Annual Cooling Cost	$50,000
Cooling Cost Reduction	25%
Annual Savings	$12,500
Life Span (years)	45
NPV =	$532,083.00
-	

Conventional Roof	
Cost/square foot	$7.60
Roof Size (sf)	101430
Installation Cost	$770,868
Savings	$0
Life Span (years)	15
NPV =	$2,989,200.00

Annual Maint Cost	
Year 1	$659
Year 2	$1,472
Year 3	$2,473
Year 4	$3,706
Year 5	$5,227
Year 6	$7,100
Year 7	$9,408
Year 8	$12,253
Year 9	$15,758
Year 10	$20,077
Year 11	$25,400
Year 12	$31,958
Year 13	$40,041
Year 14	$50,000

Terms and Abbreviations

AF – Air Force

BUR – Built Up Roof

DFW – Dallas/Fort Worth

HVAC – Heating Ventilation and Air Conditioning

LCA – Life Cycle Assessment

LCEA – Life Cycle Economic Evaluation

LM – Lockheed Martin

MBDC – McDonough Braungart Design Chemistry

POR – Period of Record

UHIE – Urban Heat Island Effect

US – United States

Bibliography

American Wind Energy Association. "Wind Energy Projects Throughout the United States." Wind Map. http://www.awea.org/projects/index.html. 1 October 2003.

Behrens, Wolfgang. President, Xeroflor Gmbh, Gross Ippener, Germany. Personal Correspondence. July, August, November, and December 2003.

Bergstrom, Bill. "Porous paving, green roofs can ease impact of development on water supplies," *Environmental News Network*, June 2002.

Bishop, Paul L. *Pollution Prevention: Fundamentals and Practice*, McGraw Hill Higher Education, Boston, 2000.

Brown, Nancy M. "Green Roofs," *Research Penn State Encyclopedia*. May 2001, Vol. 22, issue 2.

Burke, Kevin. "Green Roofs and Regenerative Design Strategies – The Gap's 901 Cherry Project." *Proceedings of Greening Rooftops for Sustainable Communities, The First North American Green Roof InfrastructureConference, Awards and Trade Show, May 29-30, 2003,* Chicago, IL. pp 1-6.

Burton, Brian. "Green roof designs are growing," *RSImag.com*, March 2003.

The Cardinal Group, Inc. "Public Benefits of Green Roofs." Article. 6 October 2003. http://www.greenroofs.ca/grhcc/public.htm.

Chang, Kenneth. "Scientists Watch Cities Make Their Own Weather," *The New York Times*, 15 August 2000, sec. F1,2.

City of Chicago. "Rooftop Garden on Chicago's City Hall." Fact Sheet. Distributed by Chicago Department of Environment. 2003-a. pp.1-4.

-----. "Urban Heat Island Initiative Pilot Project: City Hall Green Roof." Final Report. Distributed by Chicago Department of Environment. 2003-b. pp.1-44.

Cram, Gary. "Technology Rises Over History to Advance Roofing Systems," *Business Journal*, article, n.pag. 17 September 2003. http://www.bizjournals.com/sanantonio/stories/2002/08/05/focus2.html?page=1

Dawson, Donald. "Plant-Covered Roofs Ease Urban Heat," *National Geographic News*, Article, n.p. November 15, 2002. http://news.nationalgeographic.com/news/2002/11/1115_021115_GreenRoofs.

Fabrycky, W.J. and Benjamin S. Blanchard. *Life-Cycle Cost and Economic Analysis.* Englewood Cliffs, NJ: Prentice Hall, Inc., 1991.

Federal Energy Management Program (FEMP). "EO 13123 Greening the Government Through Efficient Energy Management." Executive Order. n. pag. http://www.eere.energy.gov/femp/resources/exec13123.html. June 1999.

Fedrizzi, Rick. "A Green Roof?," Buildings.com, April 2003, Vol 1, Issue 5. Online magazine article. n.pag. http://www.buildings.com/newsletters/greener_facilities/2003/apr2003.asp

Ford. "Ford Rouge Center: World's Largest Living Roof." Brochure. 2003.

Gray, Tom. "USAF Turns to Wind," Wind Energy Weekly, August 1996.

Harrison, Scott A. Facilities Engineer, Lockheed Martin Aero, Ft. Worth TX. Personal Correspondence. 27 June – 17 December 2003.

Haupt, Bertram. President, Famos GmbH, Kyritz, Germany. Personal Correspondence. July 2003.

Hoff, James L. "Life cycle costing for roofing." Article. November 5, 2003. http://www.plantservices.com/Web_First/ps.nsf/ArticleID/CBOH-5SZMN2?OpenDocument&Click=

Hutchinson, Doug and others. "Stormwater Monitoring Two Ecoroofs in Portland, Oregon, USA," *Proceedings of Greening Rooftops for Sustainable Communities, The First North American Green Roof Infrastructure Conference, Awards, and Trade Show*. Chicago, IL. May 29 - 30, 2003. pp.1-18.

Kiers, Haven. "Greenroofs: The Last Urban Frontier." Thesis. University of California at Berkeley. May 2002.

Laaly, H.O. and O. Dutt. "CBD-235. Single Ply Roofing Membranes," *Canadian Building Digest*. 7 October 2003. http://irc.nrc-cnrc.gc.ca/cbd/cbd235e.html.

Laberge, Kevin M. P.E. "Urban Oasis: Chicago's City Hall Green Roof," *Proceedings of Greening Rooftops for Sustainable Communities, The First North American Green Roof Infrastructure Conference, Awards, and Trade Show*. Chicago, IL. May 29 - 30, 2003. pp.1-10.

Lierly, Randall. AFCEE/DCD, Brooks AFB, San Antonio, TX. "Overview of Air Force Sustainable Development Program" Address to Society of American Military Engineers-Kittyhawk Post, Hope Hotel, Wright-Patterson AFB, OH. September 2003.

Liesecke, Hans-Joachim. University Professor, Institut Fur Grunplanung Und Gartenarchitektur, Universitat Hannover. “Requirments in respect of Extensive Green Roof Sites – Distinctions in the Assessments between Germany and the USA,” Xeroflor: construction techniques for arid regions and the USA, Wolfgang Behrens Systementwicklung 2003a.

-----.“Test program for construction techniques in USA.” 28 June 2003. Xeroflor: construction techniques for arid regions and the USA, Wolfgang Behrens Systementwicklung 2003b.

Liu, Karen, Ph.D. “A National Research Council Canada study evaluates green roof systems’ thermal performances,” *Professional Roofing*. Article. 14 October 2003. http://www.professionalroofing.net/article.aspx?A_ID=130.

Liu, Karen, Ph.D. and Bas Baskaran. “Thermal Performance of Green Roofs Through Field Evaluation,” *Proceedings of Greening Rooftops for Sustainable Communities, The First North American Green Roof Infrastructure Conference, Awards, and Trade Show*. Chicago, IL. May 29 - 30, 2003. pp.1-10.

McDonough, William and Michael Braungart. *Cradle to Cradle*. New York: North Point Press, 2002.

Miller, A. Richard. “Porous Pavement: Pavement that Leaks.” Commentary. 3 October 2003. http://www.millermicro.com/porpave.html

Mockler, David. Facilities Engineer, Lockheed Martin Aero, Ft. Worth TX. Electronic Message. 9 September 2003.

Monterusso, Mike. Project Director. Xeroflor America, Lansing, MI. Personal Correspondence. 11 November 2003, 19 December 2003.

National Renewable Energy Laboratories (NREL). Photovoltaic Research: Creating Electricity From an Unlimited Resource – Sunlight. Web page. http://www.nrel.gov/documents/pv_research.html. 2 October 2003.

National Weather Service. “DFW Annual Summary of Normal, Means, and Extremes.” Table of Climatic Data. 10 November 2003. http://www.srh.noaa.gov/fwd/CLIMO/dfw/normals/dfwann.html

O’Brien, Mike. “Green City.” City of Portland’s Green Building Program Quarterly Newsletter, Spring 2001, pp 1-4. 3 October 2003. http://www.sustainableportland.org/G-Rated%20Newsletter.pdf

Osmundson, Theodore. *Roof Gardens*. New York: W.W. Norton & Company, Inc. 1999.

Perry, Michael. President, Building Logics. Virginia Beach, VA. Personal Correspondence. July 2003 - January 2004a.

-----. “Green Roofs Offer Environmentally Friendly Alternative.” Plant Engineering Magazine, 2003. Article. 20 Aug 2003b. http://www.manufacturing.net/ple/index.asp?layout=article&artilceid=CA313925.

-----. “Cost Estimating Form - Building 15.” Electronic Message. 10 September 2003c.

Rowe, D. Bradley, PhD. and others. “Green Roof Slope, Substrate Depth, and Vegetation Influence Runoff,” *Proceedings of Greening Rooftops for Sustainable Communities, TheFirst North American Green Roof Infrastructure Conference, Awards, and Trade Show*. Chicago, IL. May 29 - 30, 2003. pp.1-9.

Rowls, Elizabeth, Facilities Engineer, Lockheed Martin Aero, Ft. Worth TX. Personal Correspondence. June – August, 2003.

Russell, Donald. Manufacturing Sustainability Manager, Environmental Quality Office, Ford Motor Company, Dearborn, MI. Personal Interview. July 2003.

Scheirer, David. “Built-Up Roofs Remain Popular in the West,” article. n. pag. 17 September 2003. http://www.jm.com/Roofing/Literature/TradeArticles/builtuproofs.pdf.

Scholz-Barth, Katrin. “Green Roofs: Stormwater Management From the Top Down,” *Environmental Design and Construction*, January 2001.

“Sod House on the Prairie.” Essay. n.pag. 3 October 2003. http://www.geocities.com/Heartland/Grove/5296/sodhouse.html

Solar Electric Power Association (SEPA). What are Photavoltaics?. *Inside SEPA. Article.* September 12, 2003. http://www.solarelectricpower.org/power/what_are_pvs.cfm.

“Temple University – Green Roof Proposal.” Article. n.pag. 30 July 2003. http://www.temple.edu/env-stud/seniorsem/section3C.htm

Todd, Nancy Jack and John Todd. *From Eco-Cities to Living Machines*. Berkeley, CA: North Atlantic Books, 1994.

United States Air Force (USAF). *Eco-Effective Opportunities Report for AFP4*, prepared by McDonough Braungart Design Chemistry, LLC, 2003.

-----. Sustainable Development Policy Letter. USAF Directive. Washington, 19 December 2001.

U.S. Environmental Protection Agency. "EO 13148 Greening the Government Through Leadership in Environmental Management." Legislation. April 2000. http://www.epa.gov/fedsite/eo13148.htm.

-----. "Expcite Title 33 – Navigation and Navigable Waters Chapter 26 – Water Pollution Prevention and Control Subchapter III – Standards and Enforcement." Legislation. 19 September 2003a. www.epa.gov/owow/nps/sec319cwa.html.

-----. "National Pollution Discharge Elimination System – Storm Water: Frequently Asked Questions." Information list. 30 September 2003b. http://cfpub.epa.gov/npdes/faqs.cfm?program_id=6#1.

-----. "Storm Water." Article. September 15, 2003c. http://www.epa.gov/ebtpages/watestormwater.html.

-----. "Storm Water Technology Fact Sheet – Porous Pavement." Fact sheet. EPA 832-F-99-023:(September 1999). Washington D.C.: Office of Water. 3 October 2003. http://www.epa.gov/owm/mtb/porouspa.pdf.

U.S. Green Building Council. "Leadership in Energy & Environmental Design", homepage. 15 September, 2003. http://www.usgbc.org/leed/leed_main.asp

VanWoert, Nicholas D. and others. "Green Roof Slope, Substrate Depth, and Vegetation Influence Runoff." Department of Horticulture and Department of Crop and Soil Science, Michigan State University, East Lansing, MI. Research Abstract. 2003.

Velasquez, Ralph. Engineer, Building Logics. Virginia Beach, VA. Personal Correspondence. January 2004.

Xeroflor GmbH. Gross Ippener, Germany. Personal Correspondence. July 2003.

Yin, Robert K. "Case Study Research: Design and Methods (2nd edition), Thousand Oaks, California: SAGE Publications, Inc., 1994.

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14. ABSTRACT

The United States Air Force maintains thousands of facilities around the world. Many of these facilities have asphalt built up roofs or some other less than sustainable roofing system. In an effort to find roofing systems suitable for Air Force facilities that are economically and environmentally friendly, this thesis investigated vegetated roofing as a possible alternative to conventional roofing systems. While vegetated roofs are a relatively new roofing system, they exhibit performance qualities that seem to be in line with Air Force needs.

An investigation into the feasibility of vegetated roofing technology revealed that this roofing system has many positive economic and environmental characteristics that could benefit the United States Air Force. The potential use of this technology was researched specifically for application to Building 15 at Air Force Plant 4 (AFP4) in Ft. Worth Texas. A combination of case studies, site visits, and a life cycle economic evaluation was used to compare vegetated roofing with conventional asphalt built up roofing that is typically used at AFP4. The research revealed multiple environmental benefits and few disadvantages. The life cycle costs combined with the environmental benefits of vegetated roofing show this roofing system is indeed a feasible alternative for building 15.

15. SUBJECT TERMS Roofing membranes, roof life, vegetated roofing, green roof, eco-roof, nonconventional roofing systems, hail resistance, storm water management, storm water retention, roof longevity, sustainable roofing, improved microclimate, urban heat island, reduced heat flow, thermal benefits, wildlife habitat, sedum, roof garden, intensive roof, extensive roof, stone crop, environmentally friendly roofing

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